WHOI-81-37
Copy 1

Woods Hole Oceanographic Institution

WOODS HOLE OCEANOGRAPHIC INSTITUTION
1930

TRACKING NEAR SURFACE DROGUES
USING AN ACOUSTIC TRAVEL TIME TECHNIQUE
IN SHALLOW, HIGHLY STRATIFIED WATER -
PROBLEMS AND OBSERVATIONS

by

James H. Churchill

May 1981

TECHNICAL REPORT

Prepared for the Department of Energy under Contract DE-AC02-79EV10005 and for NOAA under Contract 03-5-022-26.

WOODS HOLE, MASSACHUSETTS 02543

WHOI-81-37

TRACKING NEAR SURFACE DROGUES USING AN ACOUSTIC TRAVEL TIME TECHNIQUE IN SHALLOW, HIGHLY STRATIFIED WATER - PROBLEMS AND OBSERVATIONS

by

James H. Churchill

WOODS HOLE OCEANOGRAPHIC INSTITUTION
Woods Hole, Massachusetts 02543

May 1981

TECHNICAL REPORT

Prepared for the Department of Energy under Contract DE-AC02-79EV10005 and for NOAA under Contract 03-5-022-26.

Approved for Distribution: Valentine Worthington

Valentine Worthington, Chairman
Department of Physical Oceanography

Table of Contents

	Page
List of Tables	3
List of Figures	4
Abstract	6
1. Introduction	7
2. Problems anticipated prior to experiments	7
3. Effects of ray bending on acoustic tracking in Lake Huron	8
4. Problems due to horizontal and time dependent variation of sound velocity	23
5. Acoustic drogue and ship tracking in Lake Huron during July and August 1980	23
6. Conclusions	42
Acknowledgements	43
References	44
Appendix	A1
References	A5

List of Tables

		Page
Table 1:	Temperature profiles measured at station 8 (Figure 11).	26
Table 2:	Computed values of the rays displayed in Figure 16.	36

List of Figures

		Page
Figure 1:	Isotherm contours for a Lake Huron transect (from Csanady and Pade, 1968).	9
Figure 2:	Sound velocity profile calculated from a typical temperature profile in Lake Huron.	10
Figure 3:	Acoustic rays calculated using the sound velocity profile of Fig. 2. Departure angles (as measured from the horizontal) range from 0.2 to 0.28 radians (11.5° - 16.0°) in steps of .02 radians.	11
Figure 4:	Acoustic rays calculated using the sound velocity profile of Fig. 2. Departure angles range from .2298 to .2300 radians in steps of .0001 radians.	13
Figure 5:	Four possible ray paths for sound entering the shadow zone.	14
Figure 6:	The lower graph shows the percent difference (error) between the path length of an SBR ray and a straight line ray from a bottom source to the surface. The upper graph displays the grazing angle at each reflection for the SBR ray. The water depth is 60 m and the inflection range is 600 m.	16
Figure 7:	Same as Figure 6 except for an inflection range of 300 m.	17
Figure 8:	Errors in position components due to receiving an SBR ray and assuming straight line travel. Parameters are: water depth = 60 m, inflection range = 300 m, baseline length = 1000 m, drogue vel = 1 m/s, initial x,y = (500 m, 200 m).	19
Figure 9:	Errors in position components due to receiving an SBR ray and assuming straight line travel. Parameters are: water depth = 60 m, inflection range = 300 m, baseline length = 1000 m, drogue vel = 1 m/s, initial x,y = (0 m, 200 m).	20
Figure 10:	Errors in position components due to receiving an SBR ray and assuming straight line travel. Parameters are: water depth = 60 m, inflection range = 600 m, baseline length = 1000 m, drogue vel = 1 m/s, initial x,y = (500 m, 200 m).	21
Figure 11:	Lake Huron field project site. Dots labeled 1-10 depict flag station locations (the tracking ship was tied to Sta. 8 during the experiments). X's labeled A, B and C mark bottom transponder locations.	25

Figure 12:	Acoustic rays calculated using the August 14 temperature profile of Table 1. Departure angles (as measured from the horizontal) range from .246 radians to .256 radians (14.1-14.7 deg) in steps of .002 radians.	27
Figure 13:	Ship positions, cluster of dots, calculated from travel time data of the August 14 experiment. Points A, B and C mark the respective transponder locations.	29
Figure 14:	Ship cycle round trip travel times recorded during the August 13 experiment. Ship transducer depths are noted.	30
Figure 15:	Ship cycle round trip travel times recorded during the August 14 experiment.	31
Figure 16:	Acoustic rays calculated using the August 14 temperature profile of Table 1. Ray 1, 2 and 3 are transmitted and received between a bottom transponder at 60 m depth and a transducer at 20 m depth and 1.2 km range. Ray 4 is transmitted by the transponder at too shallow an angle to be received at the transducer's depth.	34
Figure 17:	Ship position components vs. time calculated using the August 14 travel time data displayed in Figure 15. The lines are of least-squares linear regressions.	39
Figure 18:	Acoustic rays, reflected at the thermocline, calculated using the July 14 and August 14 temperature profiles of Table 1.	41
Figure 19:	Geometry of a drogue tracking system with three transponders.	A2

Abstract

During July and August of 1980 near surface water velocities of Lake Huron were measured by tracking drogues, equipped with sonobuoys, using an acoustic travel time technique. Prior to these experiments difficulties associated with acoustic ray bending in the shallow, highly stratified environment were anticipated. Simple models were developed to predict the errors in drogue position and velocity determination resulting from ray bending. During the experiments round trip travel times of acoustic pulses transmitted between three bottom transponders and a transducer (lowered from a ship) were recorded. These combined with ray diagrams strongly suggested that, for a separation between the transducer and a bottom transponder of about 1.2 km, pulses which were detected first traveled by two paths, that of an inflected ray and that of a ray trapped beneath the thermocline. The error in position and velocity determination associated with these paths was 1 to 2%. Evidence also indicated that increased thermocline depth resulted in decreased tracking range.

1. Introduction

During July and August of 1980 our research group measured near surface water velocities in Lake Huron by tracking surface and submerged drogues. An acoustic navigation system, employing a travel time technique, was used for drogue tracking.

To our knowledge, this system had never been used in a shallow, highly stratified environment such as Lake Huron. Difficulties associated with ray bending effects were anticipated. This report deals with these difficulties and their probable effect on velocity determination. Sections 2-4 were written prior to the experiments and discuss problems as they were foreseen. Section 5 briefly discusses the experiments and the insight gained from them.

A complete knowledge of the acoustic navigation system and the drogues is assumed. The navigation system is briefly described by the Appendix. A more complete account is given by Churchill, et al. (1981).

A comprehensive report of the scientific results of the project is being prepared.

2. Problems anticipated prior to experiments

In Lake Huron the bottom transponders will be deployed about 8 km offshore in approximately 60 m of water. Lake Huron has a characteristically sharp thermocline and an upwelled front may be expected in the vicinity of the transponders. Previously, the acoustic navigaton system has been used in deep water or well mixed shallow water; no report of use in a shallow, stratified environment, such as Lake Huron, has been located.

The acoustic navigation system at present relates the measured travel time to the slant range by a formula whose coefficients are calculated using ray analysis and the local sound velocity profile. The sound velocity profile is assumed constant horizontally and in time, a good approximation in the deep ocean. In Lake Huron, where the sound velocity is predominantly determined by temperature, there is noticeable horizontal and time variation. Figure 1 displays horizontal variation due to an apparent downwelling. The variation with time can be significant during periods of strong and shifting winds (Murthy and Blanton, 1975).

The presence of a thermocline will cause sound rays transmitted from the bottom transponders to bend away from the surface. This will, of course, produce the classical "shadow zone" where reception of the direct ray from the transponder will be impossible. With this in mind, important considerations for the upcoming field project are: how far from the transponder will the direct ray be detectable; and, will ship and drogue tracking be feasible within the shadow zone?

3. Effects of ray bending on acoustic tracking in Lake Huron

Figure 2 displays a sound velocity profile calculated form a typical temperature profile in Lake Huron (Csanady and Pade, 1968). This profile was used to calculate acoustic ray paths emanating from a bottom source (Figure 3). (Note: The wavelengths of pulses used by the acoustic navigation system range from 11 cm to 23 cm; thus ray analysis can be meaningfully applied.) These rays suggest a shadow zone begining at

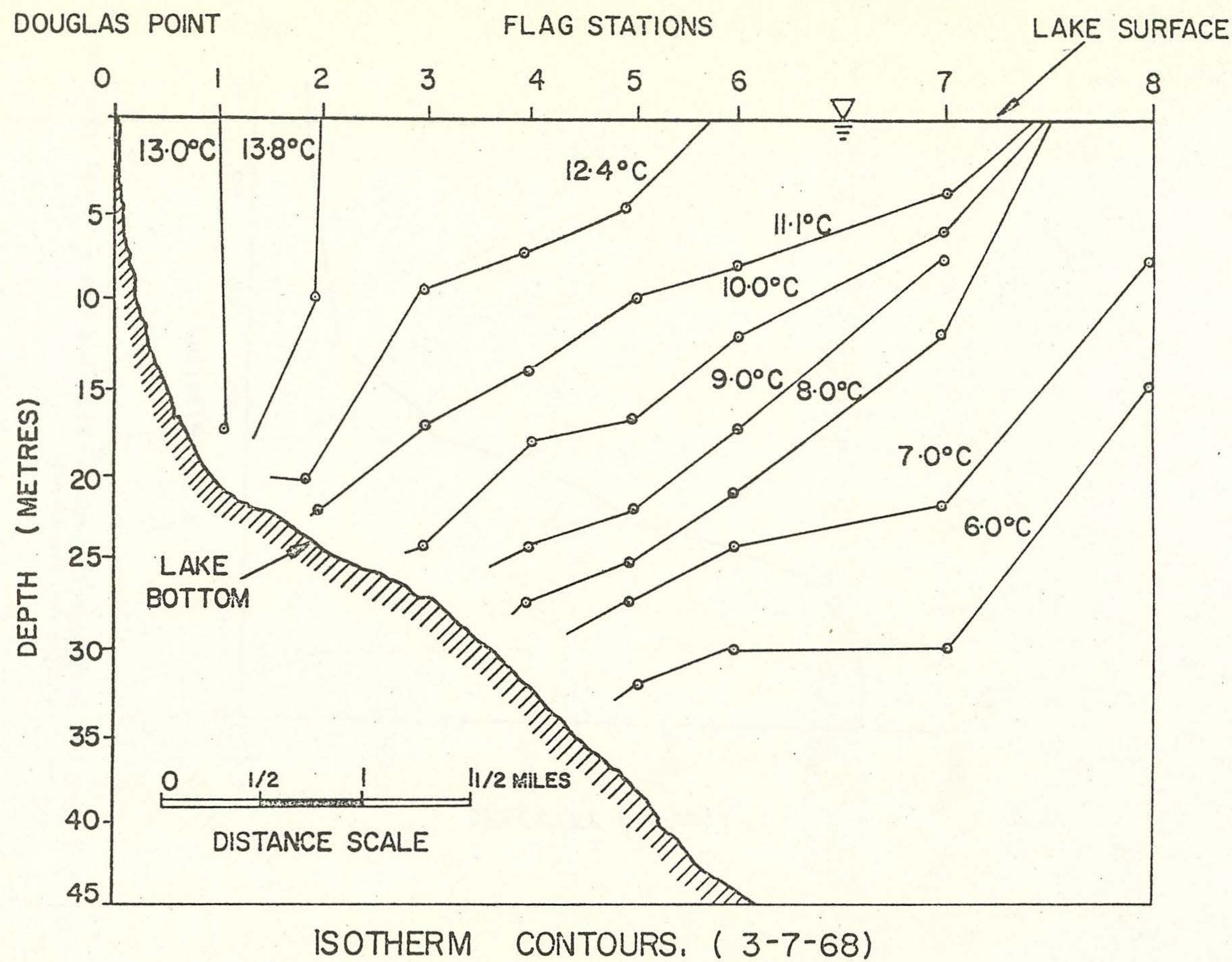

Figure 1. Isotherm contours for a Lake Huron transect.
(From Csanady and Pade, 1968)

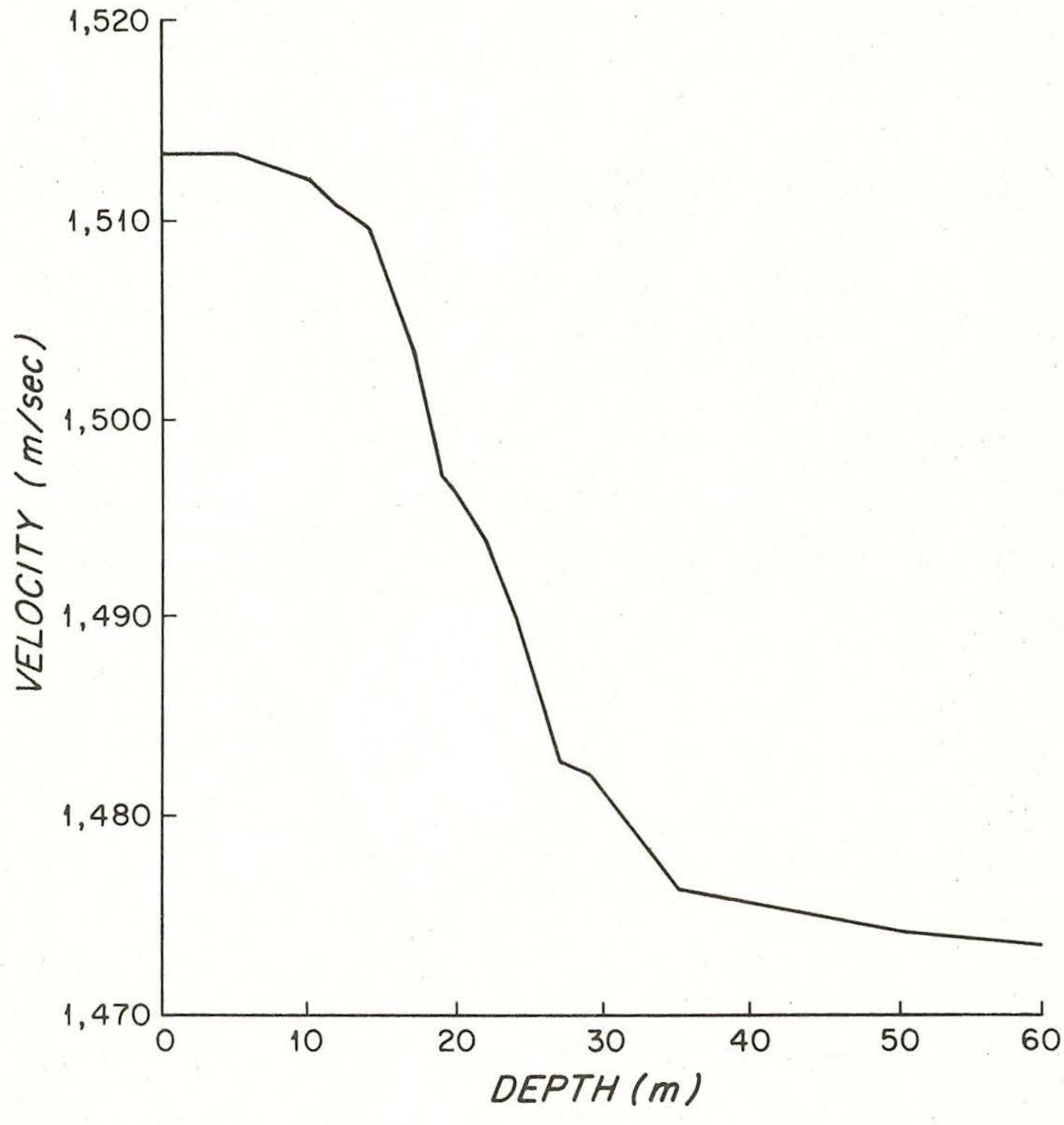

Figure 2: Sound velocity profile calculated from a typical temperature profile in Lake Huron.

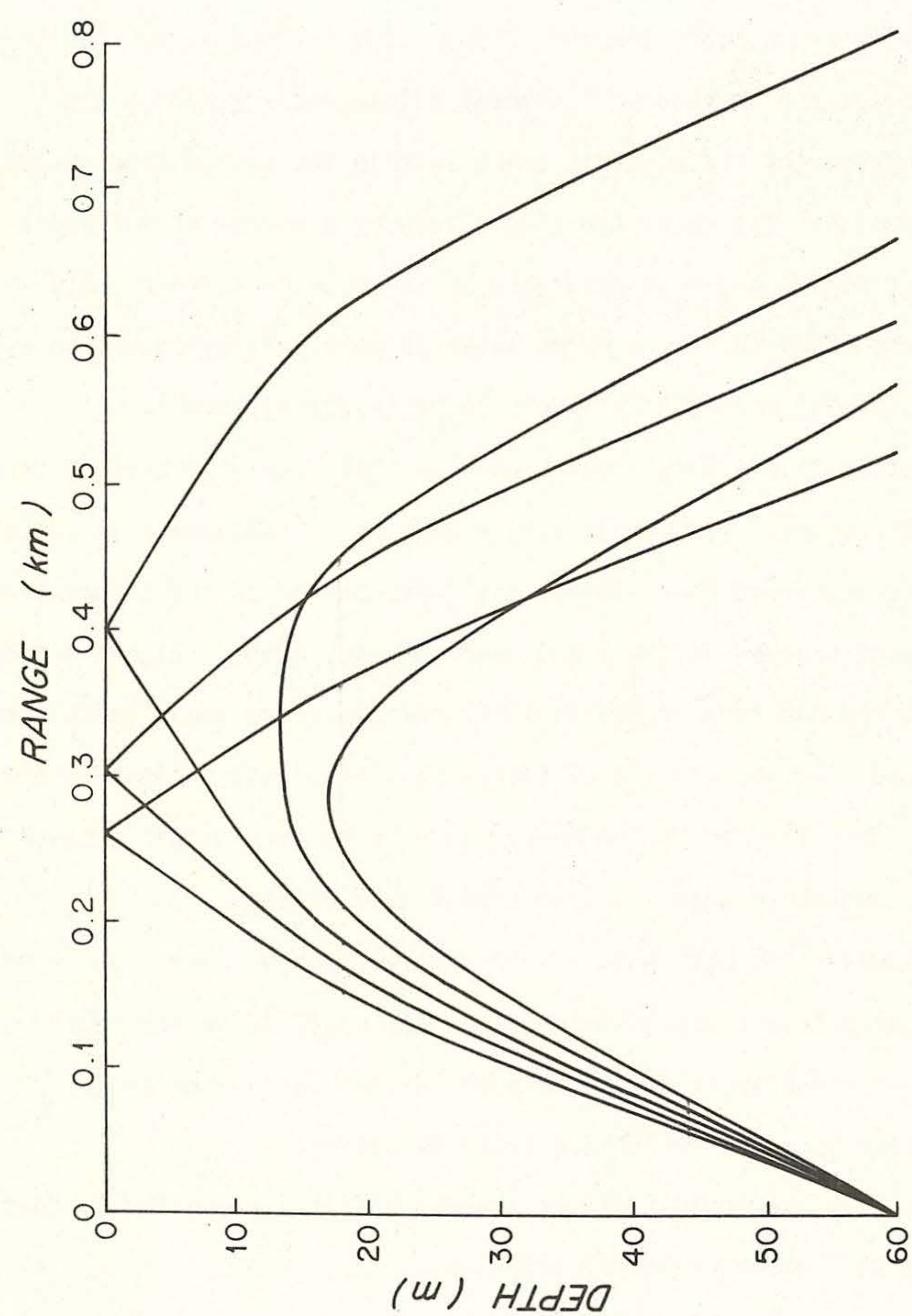

Figure 3: Acoustic rays calculated using the sound velocity profile of Fig. 2. Departure angles (as measured from the horizontal) range from 0.2 to 0.28 radians (11.5° - 16.0°) in steps of .02 radians.

about 0.5 km from the source. (For convenience this distance at which the direct ray from the bottom is no longer detectable at the surface will be referred to as the inflection range.) Because we wish to track the drogues for distances of several kilometers, detection and intepretation of the acoustic signal within the shadow zone is imperative.

The signal may enter the shadow zone by a number of different paths. The most direct and most desirable of these is by forward scattering due to volume scatters. Lake Huron water is particularly clear, however, so the scattering strength is likely to be relatively small.

Another fairly direct path would be that of a near surface trapped ray. If the near surface is well mixed, as it frequently is in Lake Huron (Csanady and Pade, 1968), a slight portion of the transmitted sound may become trapped in the mixed layer (Morse, 1950). Figure 4 displays a trapped ray and rays of nearly identical departure angle calculated from the sound velocity profile of Figure 2. These rays indicate the energy of the sound trapped in the mixed layer to be very slight because the span of departure angle is less than 0.0002 radians.

A similar ray path with a potentially stronger signal would be that of a near bottom trapped ray. Such a ray would leave the source at a small departure angle and be trapped in the near bottom water by refraction into and reflection from the bottom.

Finally, the longest of the obvious possible ray paths is that of a surface and bottom reflected (SBR) ray.

Figure 5 presents the four possible ray paths described above. It is apparent that relating the slant range to the travel time of these rays

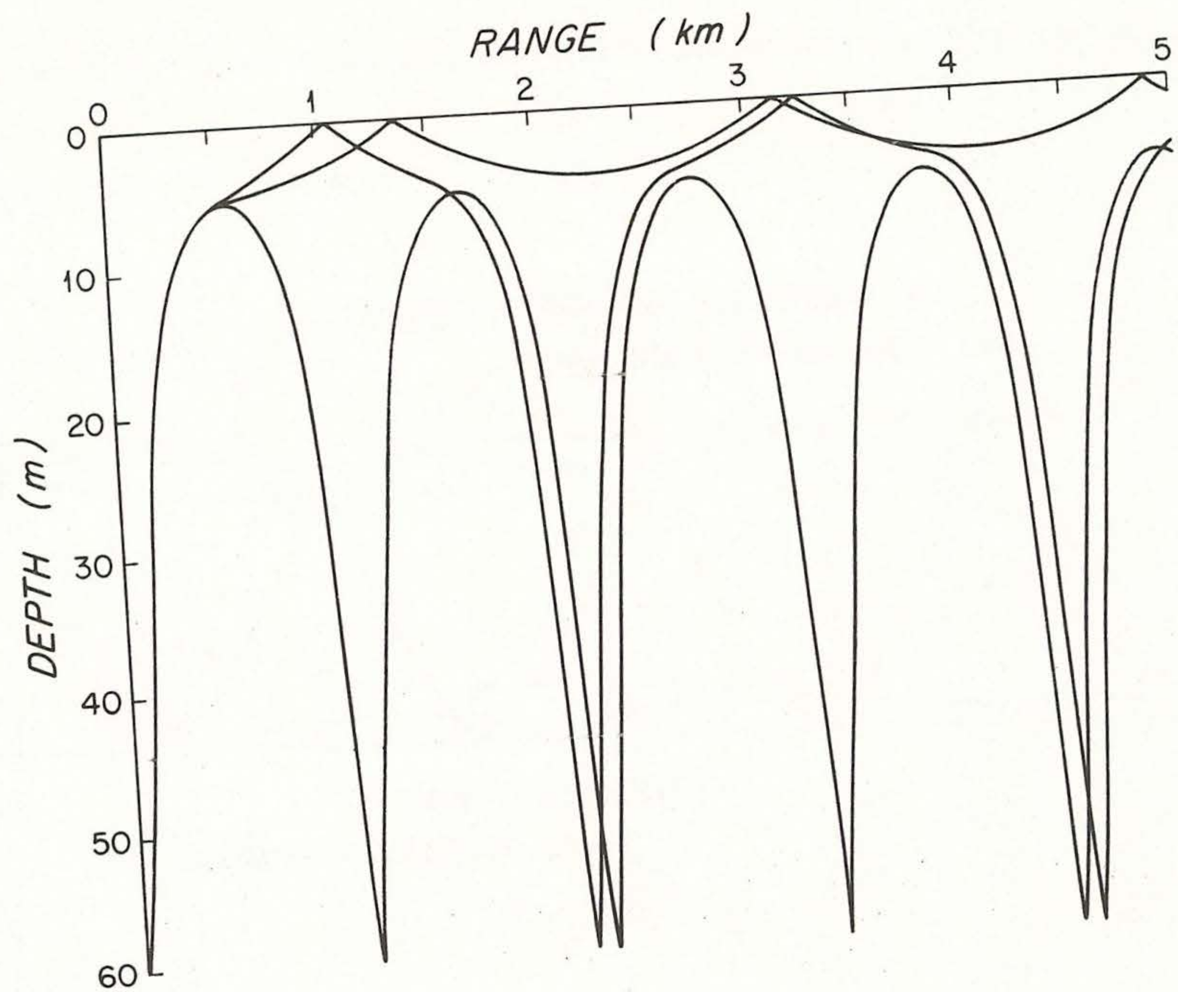

Figure 4: Acoustic rays calculated using the sound velocity profile of Fig. 2. Departure angles range from .2298 to .2300 radians in steps of .0001 radians.

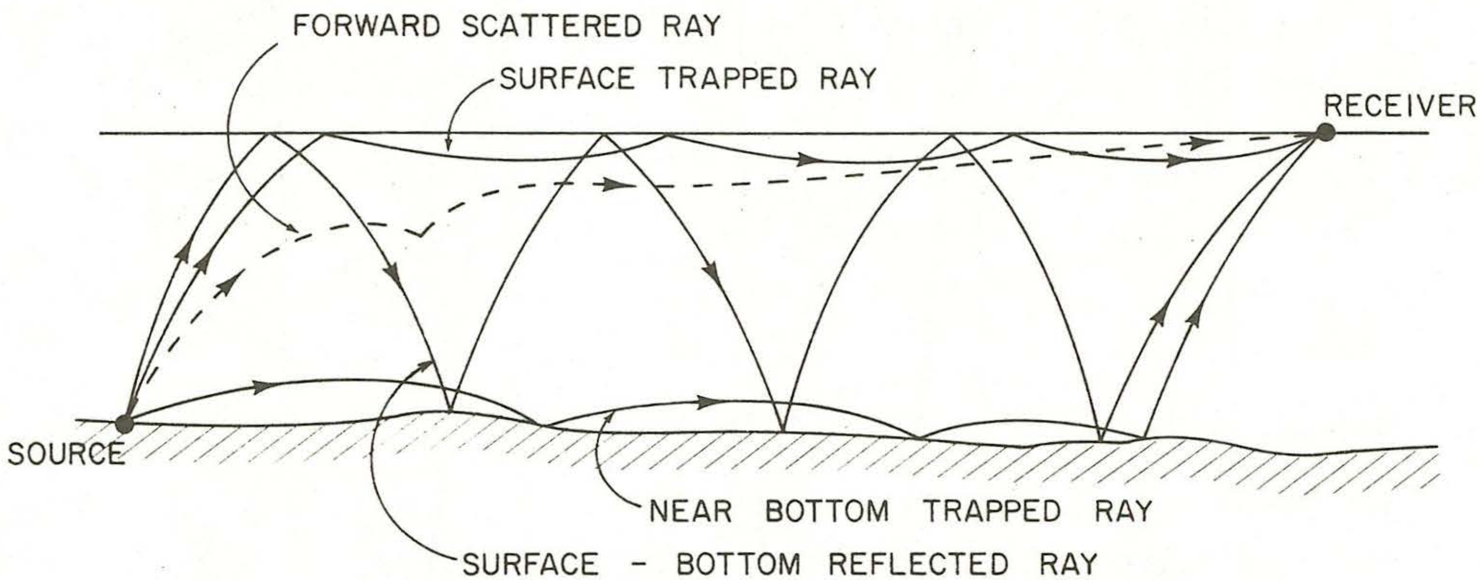

Figure 5. Four possible ray paths for sound entering the shadow zone.

by use of ray analysis is nearly impossible. The remainder of this section will deal with the effect of using the most straightforward alternative method. This is to assume that the detected signal had traveled in a straight line at the average sound velocity of the water column. For such an approximation the path difference between the assumed line of travel and the actual acoustic path would be greatest for an SBR ray. Calculations of errors due to receiving an SBR ray and assuming straight line travel would thus approximate error figures for the "worst" case. (Note that travel time is actually the measured parameter; but, for the approximations presented in this section, relative errors of travel time and path will be considered roughly the same.)

A simple method for estimating the path-length difference between the straight line from the source to the surface and the SBR ray has been devised. Between reflections, the rays, which are approximated as straight lines, are not allowed to travel horizontal distances greater than the specified inflection range. Using this method the percent difference (error) between the straight line distance and SBR path length together with the grazing angle of reflection have been calculated at incremental distances from the source. The results for two values of inflection range are displayed in Figures 6 and 7. Note the obvious jump in error at odd multiples of the inflection range due to the addition of one surface and one bottom reflection. Note that the error for the shorter inflection range of 300 m is consistently less than 4% at horizontal ranges from the source of greater than 1 km. For the longer

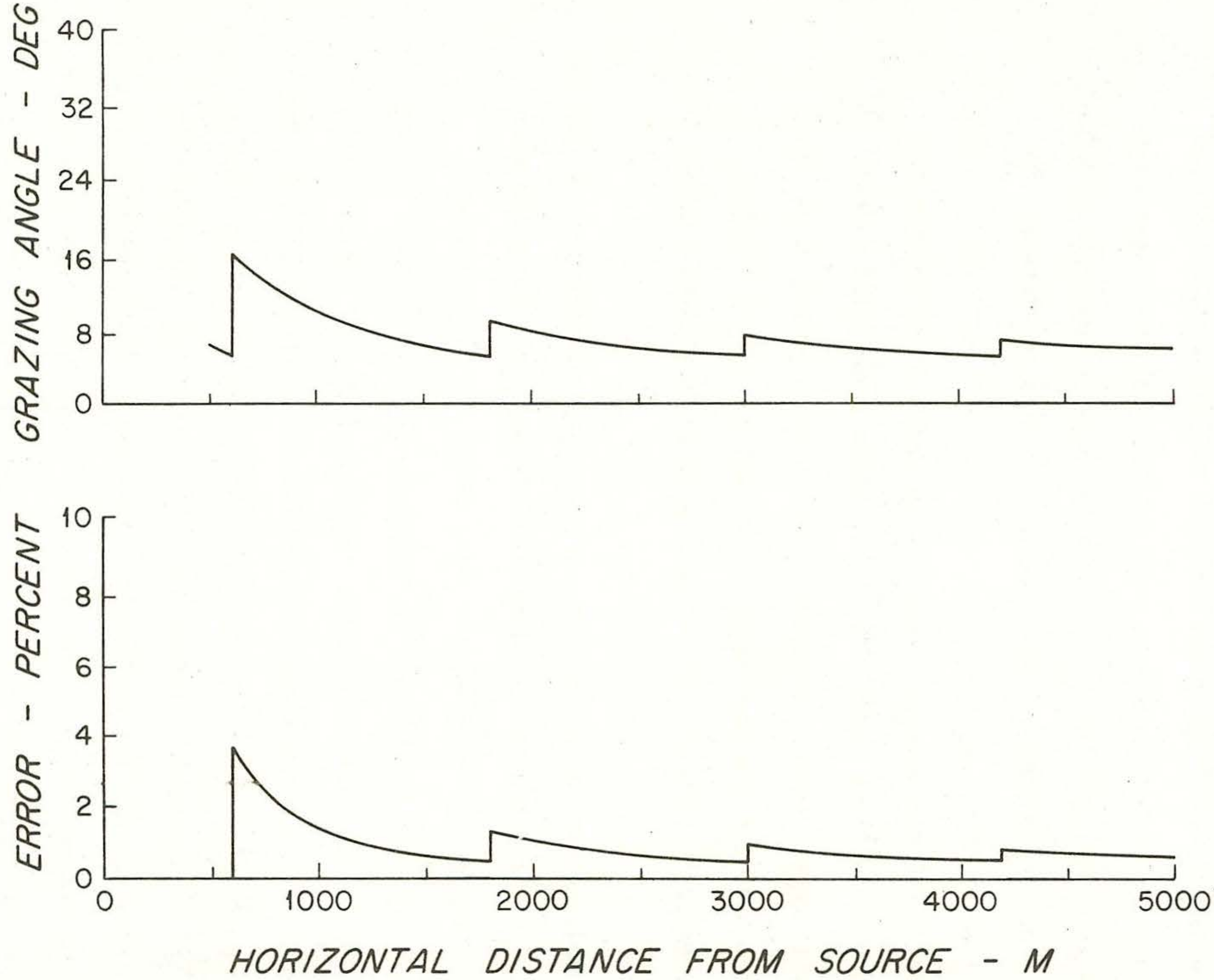

Figure 6: The lower graph shows the percent difference (error) between the path length of an SBR ray and a straight line ray from a bottom source to the surface. The upper graph displays the grazing angle at each reflection for the SBR ray. The water depth is 60 m and the inflection range is 600 m.

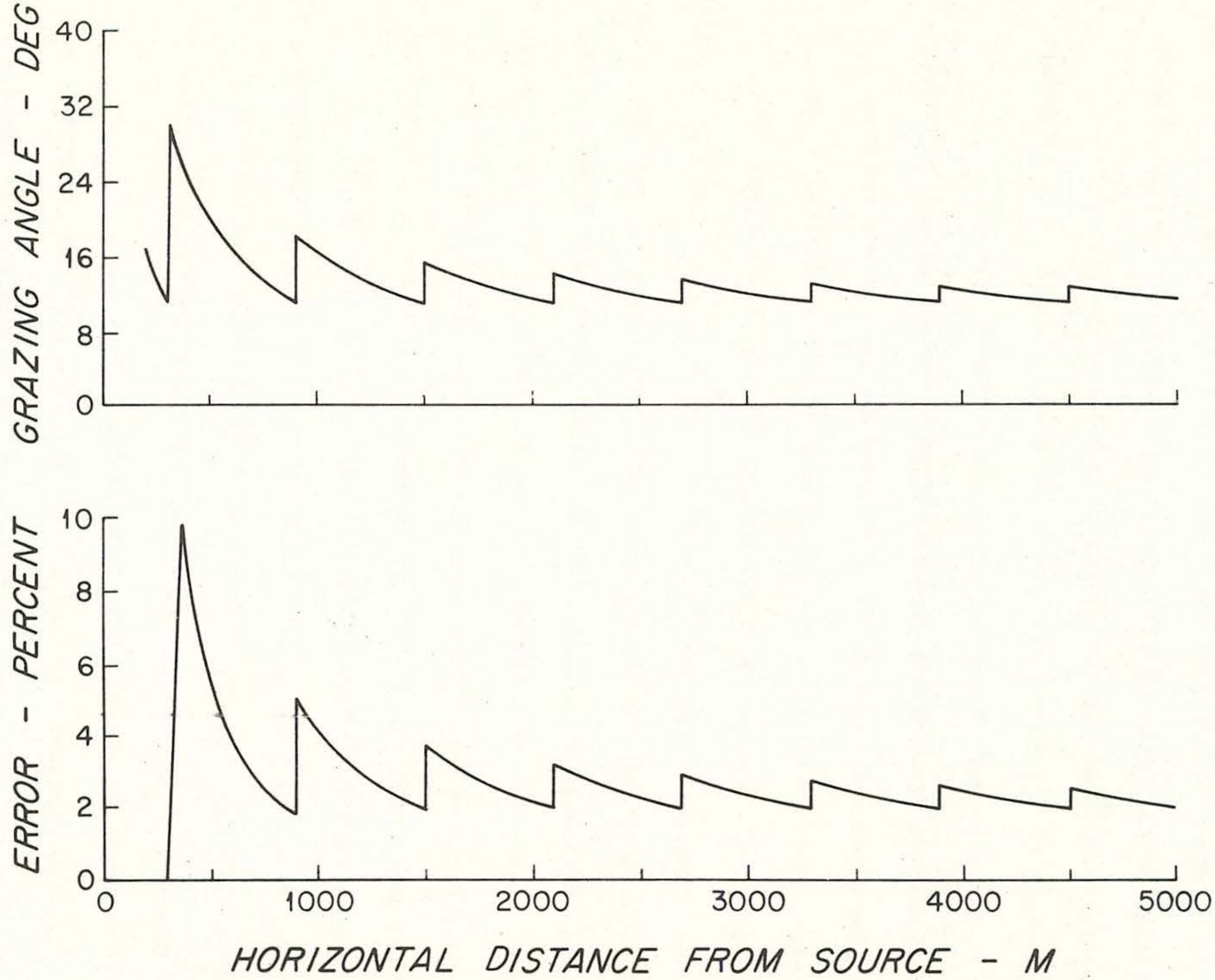

Figure 7: Same as Figure 6 except for an inflection range of 300 m.

inflection range of 600 m, which is about the length we should encounter in Lake Huron, the error is mostly less than 1%.

With regard to upcoming field project the effect the error in slant range has on the measured velocity is most important. Drogue velocity components are taken as the slopes of the least squares linear regressions of position components with time. Generally fixes during a one to two hour period are included in the regressions.

A computer program has been developed which estimates the trend of position component error due to receiving an SBR ray and assuming straight line travel. For a given drogue velocity, initial drogue position, and baseline (distance between the two transponders) the program computes drogue positions as a functon of time. At each position the path length of the SBR ray from each transponder is computed by the method previously described. By considering these path lengths to be slant ranges, the "erroneous" position is computed. Figures 8, 9 and 10 display error in position components as a function of time for three situations. Note the linear fit of position component error vs. time is at most 2 cm/s for the velocity of 1 m/s. There are marked discontinuities in the position component error at locations where one or both of the rays has undergone an additional bottom and surface reflection. In the nonidealized, real environment these discontiuities will probably be absent or of reduced magnitude.

Another consideration which will be crucial in the upcoming field project is: to what range will the acoustic signal be detectable? In a previous application we were able to track the drogues to a slant range

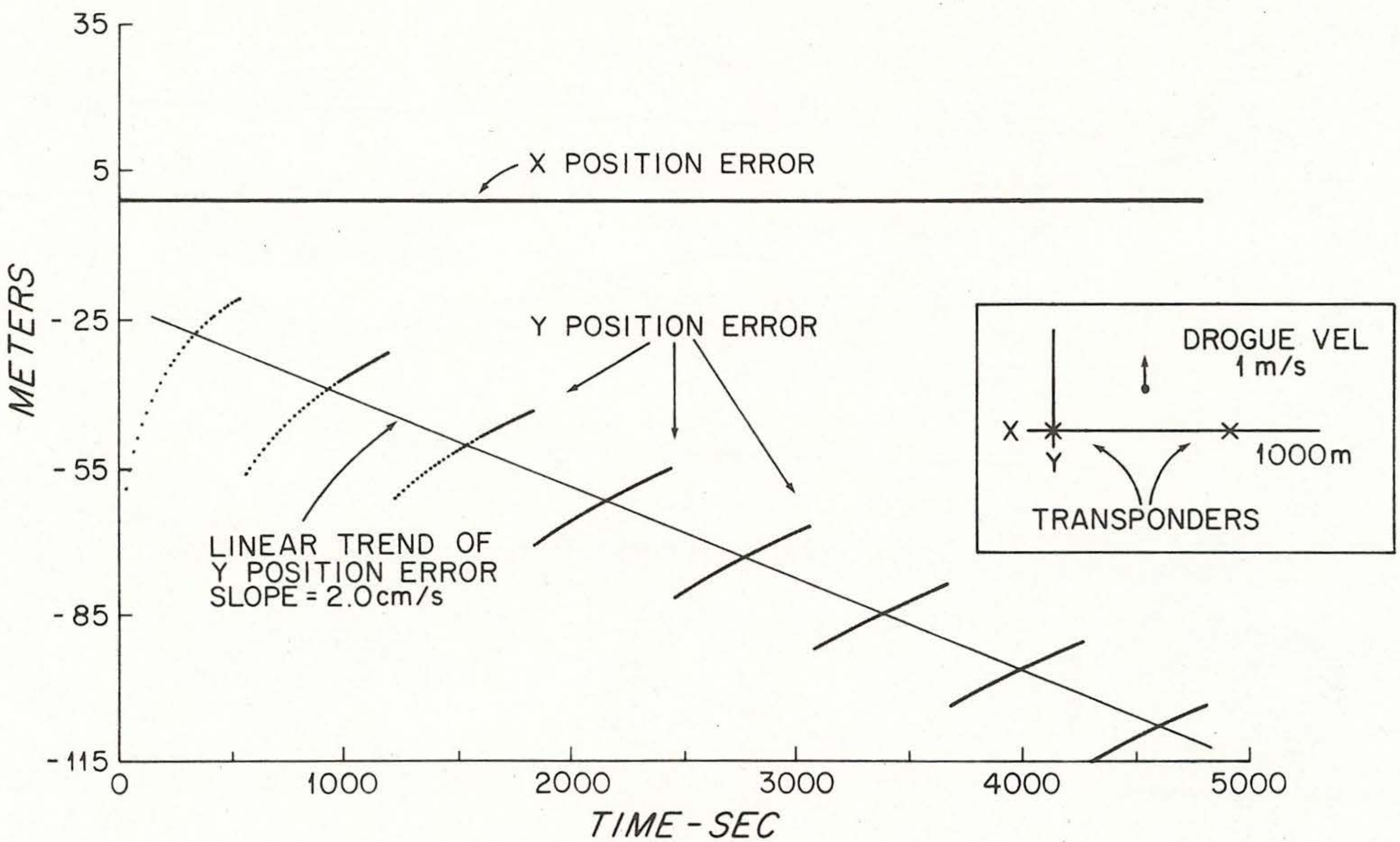

Figure 8: Errors in position components due to receiving an SBR ray and assuming straight line travel. Parameters are: water depth = 60 m, inflection range = 300 m, baseline length = 1000 m, drogue vel = 1 m/s, initial x,y = (500 m, 200 m).

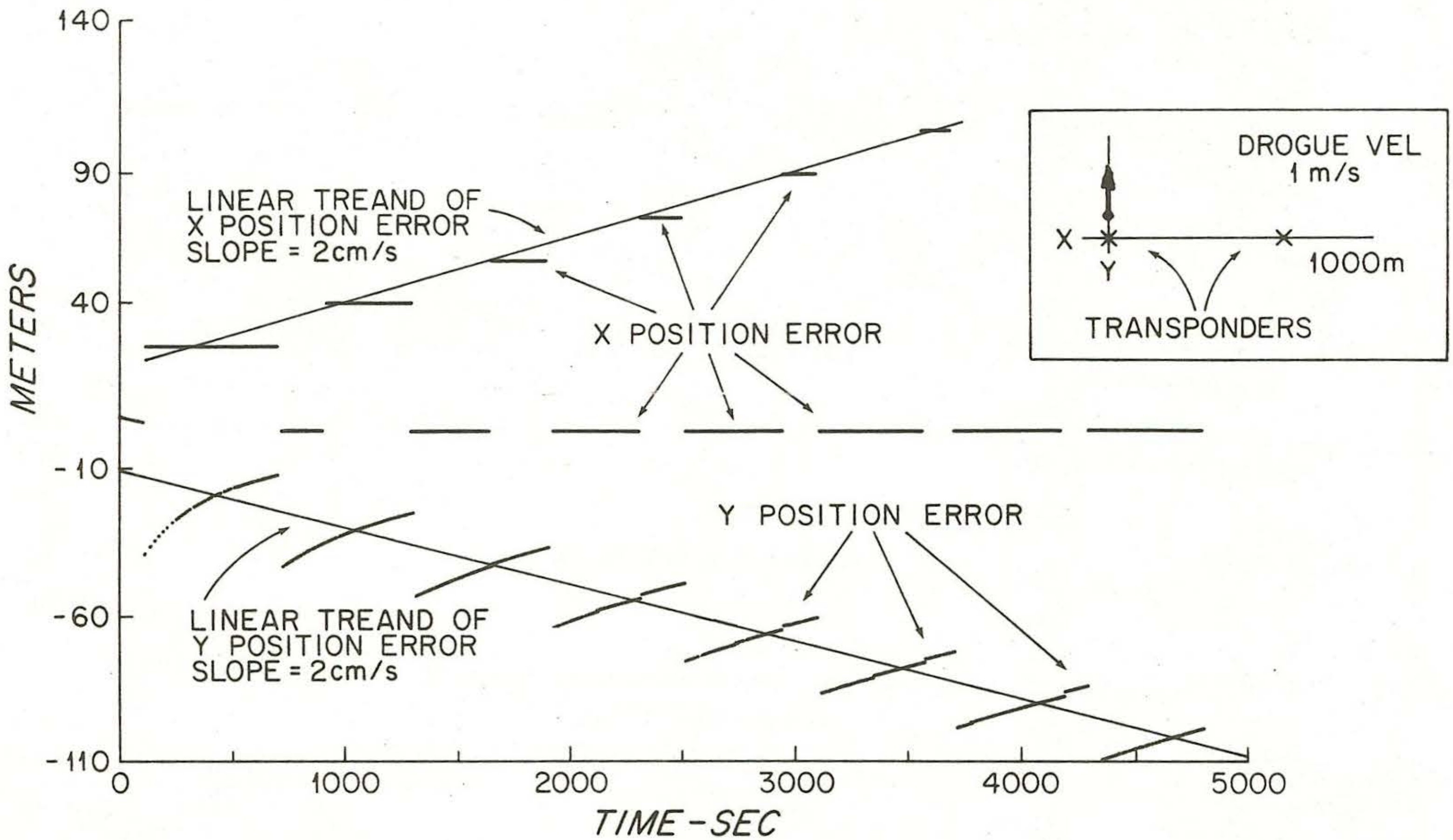

Figure 9: Errors in position components due to receiving an SBR ray and assuming straight line travel. Parameters are: water depth = 60 m, inflection range = 300 m, baseline length = 1000 m, drogue vel = 1 m/s, initial x,y = (0 m, 200 m).

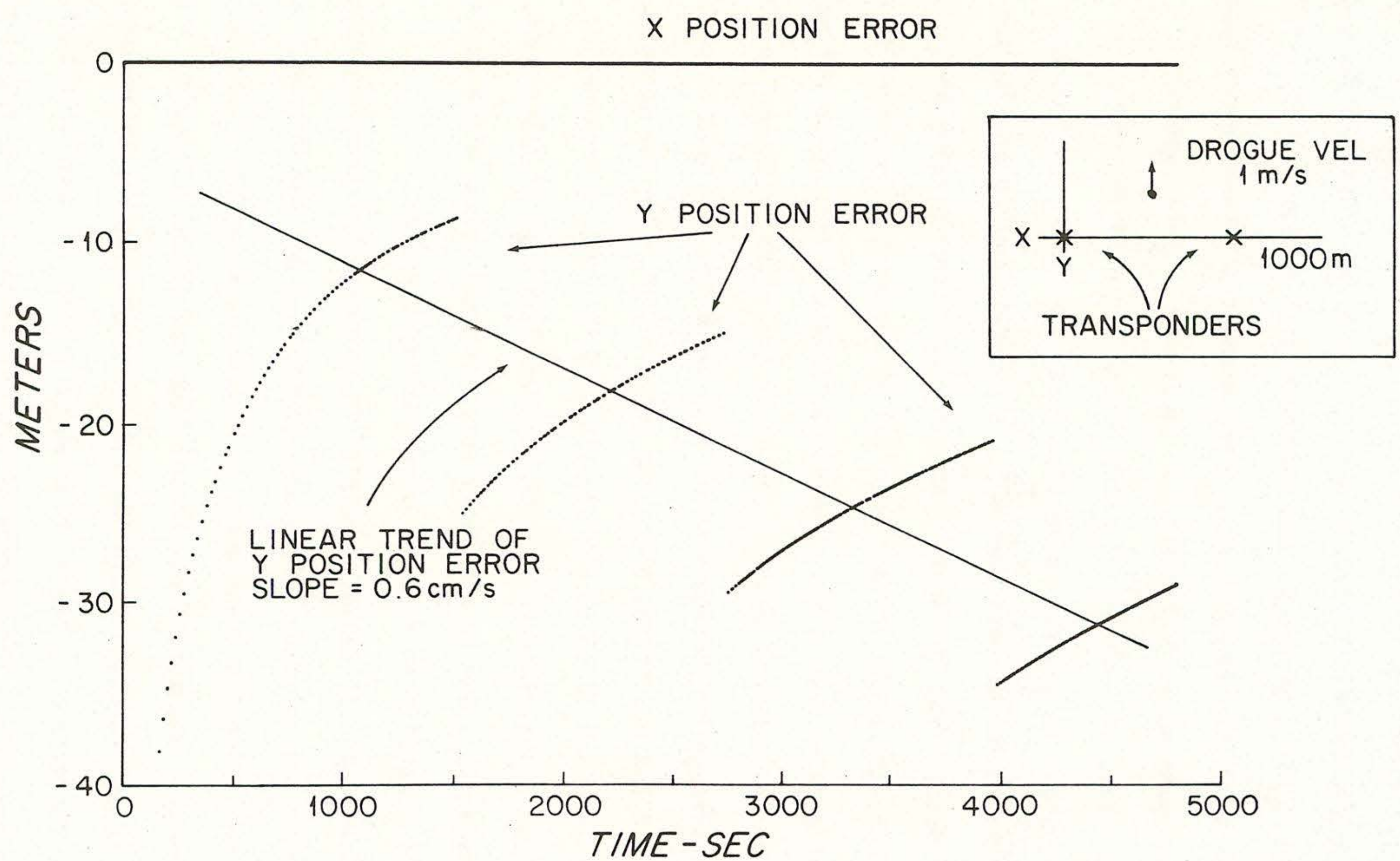

Figure 10: Errors in position components due to receiving an SBR ray and assuming straight line travel. Parameters are: water depth = 60 m, inflection range = 600 m, baseline length = 1000 m, drogue vel = 1 m/s, initial x,y = (500 m, 200 m).

of about 7 km from the transponder net. An SBR ray will, of course, experience additional attenuation due to signal loss and spreading on reflection. For a bottom reflection the signal attenuation is a function of bottom material and roughness. Lake Huron has a sandy-rocky bottom which is a good acoustic reflector. Liebermann (1948) reported a reflection loss of 4 db from a sandy bottom for a 24 khz signal at a 10° grazing angle. In general reflection loss increases with frequency and, for grazing angles of less than 10°, is proportional to grazing angle (Marsh, 1966). Note in Figure 7 that the estimated grazing angle for a 600 m inflection range is less than 10° at horizontal distances from the source of greater than 1 km. The signal loss due to surface reflection will be proportional to grazing angle and sea state. Liebermann (1948) found an average reflection loss of 3 db at 30 khz for wave heights of between 0.2 and 0.8 ft and a grazing angle of 8°. For the upcoming field project, in which 10 to 13 khz signals will be used, a reasonable estimate of signal loss for an SBR ray would be 3db per reflection. The transmission loss due to spherical spreading and volume attenuation at ranges of greater than 2 km is approximately 2 db/km.

At Lake Huron it would be helpful to estimate the tracking range and investigate the ray path before attempting to track the drogues. I would suggest deploying one transponder and steaming away from it while simultaneously monitoring the travel time and signal strength. A sudden drop in signal strength would indicate passage into the shadow zone. From the corresponding travel time an estimation of the inflection range would be possible. The absence of a simultaneous jump in travel time would indicate the reception of a forward scattered ray. If there was a simultaneous travel time jump its magnitude would provide a clue as to which ray path was being detected. This could be used to develop a more sophisticated method of calculating the slant range from the travel time.

4. Problems due to horizontal and time dependent variation of sound velocity

The sound velocity profile of Figure 2 is typical for Lake Huron. The total variation in sound velocity is 30 parts in 1500 or 2%. The maximum error due to horizontal or time dependent variation in temperature structure would thus be of the same magnitude as that just analyzed due to ray bending.

5. Acoustic drogue and ship tracking in Lake Huron during July and August 1980

A net of three transponders was used for the Lake Huron experiments. After the second transponder deployment on July 14, an attempt was made to simultaneously record reply pulse signal strength and travel time while steaming away from the transponder. Unfortunately strip chart recording of the signal strength did not produce any usable results. This was because inductive pickup of the outgoing pulse drove the needle off axis when the strip chart was set to a scale sensitive enough to measure the incoming pulse. The reply pulse was consistently received to a maximum round trip travel time of about 11 seconds. This corresponds to a maximum reception slant range of about 8 km, which is approximately equal to that measured in a previous deep ocean experiment (Churchill, _et al._, 1981). The third transponder was deployed on July 15.

Acoustic drogue tracking did not commence until August 12 because of problems with the motor of the ship used for tracking. Experiments were conducted on six separate days from August 12 to August 21. During tracking the ship was tied to a mooring within the transponder net in about 60 m of water at 8 km offshore (Figure 11). A rapid succession of "bleps" heard on the audio monitor of the incoming signal indicated that reflected and multiple-reflected pulses were being received.

The temperature profiles taken during the August 13 and August 14 experiments, listed in Table 1, are typical of profiles taken during all experiments. The mixed layer was about 14m deep and the thermocline was relatively narrow. Profiles taken along a transect of flag stations (Figure 11) indicated that isotherms in the vicinity of the transponder net were nearly horizontal. The ray diagrams to be presented in this section, which were calculated assuming a horizontally constant sound velocity profile, are thus reasonably valid.

A ray diagram calculated using the August 14 profile is displayed in Figure 12. Note that a ray entering the mixed layer may travel for a great distance in the layer. Based on this Figure one may infer an inflection range in excess of 1.2 km. Only a small portion of the transmitted energy enters the mixed layer as a direct ray, however. The direct rays which reach the surface at a range of greater than 450 meters span a departure angle range of 0.004 radians. For an omnidirectional source this represents only 0.06% of the total transmitted energy. Thus,

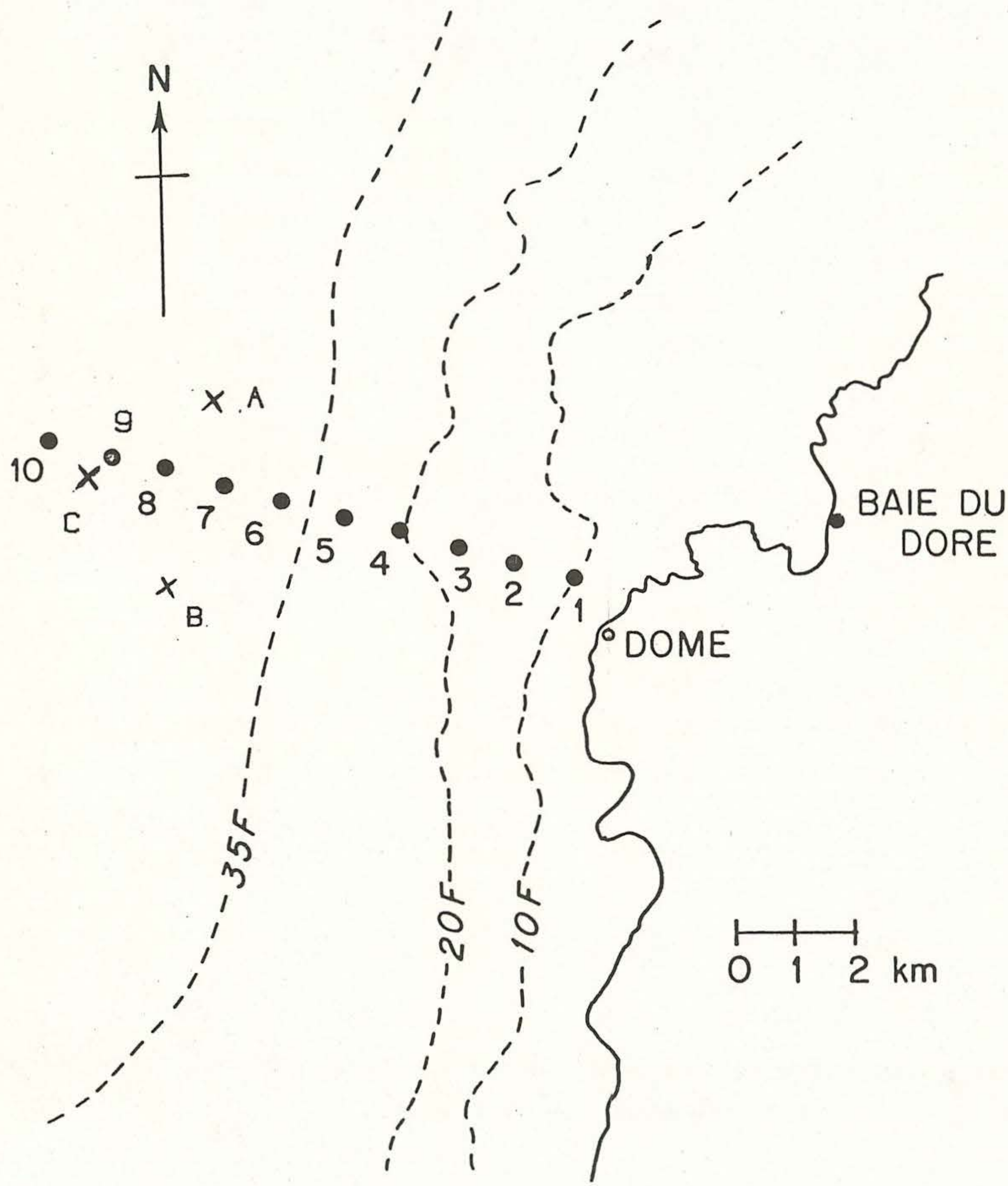

Figure 11. Lake Huron field project site. Dots labeled 1-10 depict flag station locations (the tracking ship was tied to Sta. 8 during the experiments). X's labeled A, B and C mark bottom transponder locations.

Table 1

Temperature profiles measured at station 8 (Figure 11).

Depth-m	July 14 temp °C	Aug. 13 temp °C	Aug. 14 temp °C
1	12.5	20.9	20.0
2	12.5	20.4	20.0
4	12.5	20.2	20.0
6	11.0	19.3	20.0
8	10.5	19.2	19.8
10	10.0	19.2	19.8
12	9.9	19.1	19.8
14	9.7	18.9	19.5
16	8.7	12.6	17.0
18	7.9	11.3	12.0
20	7.0	9.9	10.8
22	6.0	9.1	9.0
24	5.9	8.3	7.7
26	5.8	8.1	7.1
28	5.5	7.6	6.8
30	5.4	7.0	6.6
35	-	6.4	6.0
40	5.0*	6.1	5.2
45	-	6.1	-
60	4.6*	5.8*	5.0*

*These values were not measured. They were included for the calculation of ray diagrams with the source at 60m depth.

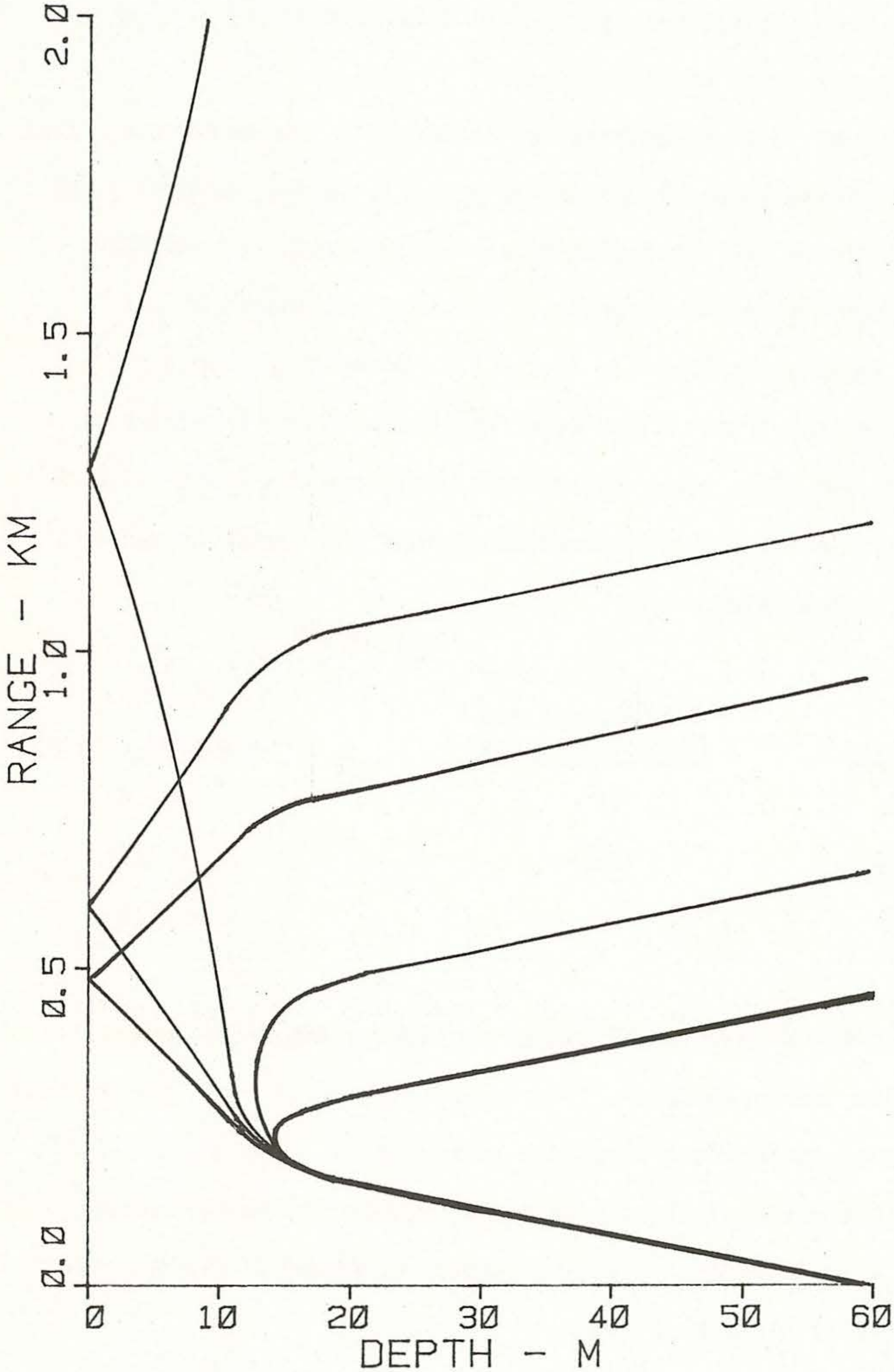

Figure 12. Acoustic rays calculated using the August 14 temperature profile of Table 1. Departure angles (as measured from the horizontal) range from .246 radians to .256 radians (14.1-14.7 deg) in steps of .002 radians.

at distances from the source greater than 450m most of the transmitted energy is trapped below the thermocline.

On August 13 an experiment was conducted to determine the effect of the depth of the ship's tranducer on acoustic navigation during the ship cycle. (There are two cycles of navigation, ship and sonobuoy; these are described in the Appendix.) The ship was moored at the approximate location as shown in Figure 13. Round trip ship to transponder to ship travel times were recorded with the tranducer at depths of 5m, 10m (just above the thermocline), and 20m (just below the thermocline). The number of interrogations and the number of missed replies are listed below:

Depth	# Interrogations (Outgoing pulses)	# missed replies
5m	14	8
10m	123	57
20m	57	4

Note that the proportion of missed replies to interrogations decreased with increased depth. The round trip travel times to and from the bottom transponders are displayed in Figure 14. The scatter in travel time was obviously less with the transducer below the thermocline than in the mixed layer. For all subsequent experiments the transducer was maintained at a depth of 20m.

The ship cycle round trip travel times during the August 14 experiment are displayed in Figure 15. The computed ship positions are

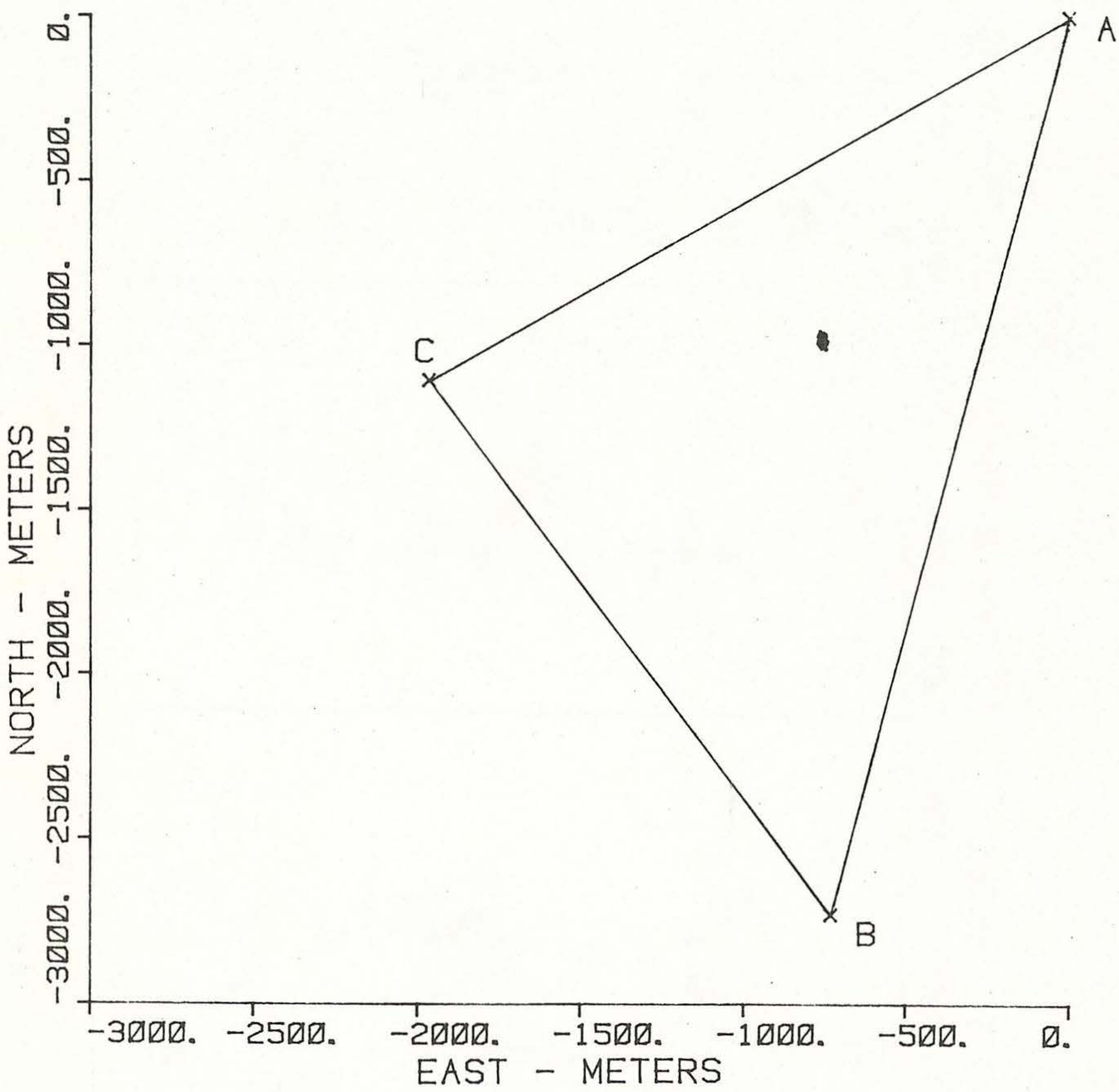

Figure 13. Ship positions, cluster of dots, calculated from travel time data of the August 14 experiment. Points A, B and C mark the respective transponder locations.

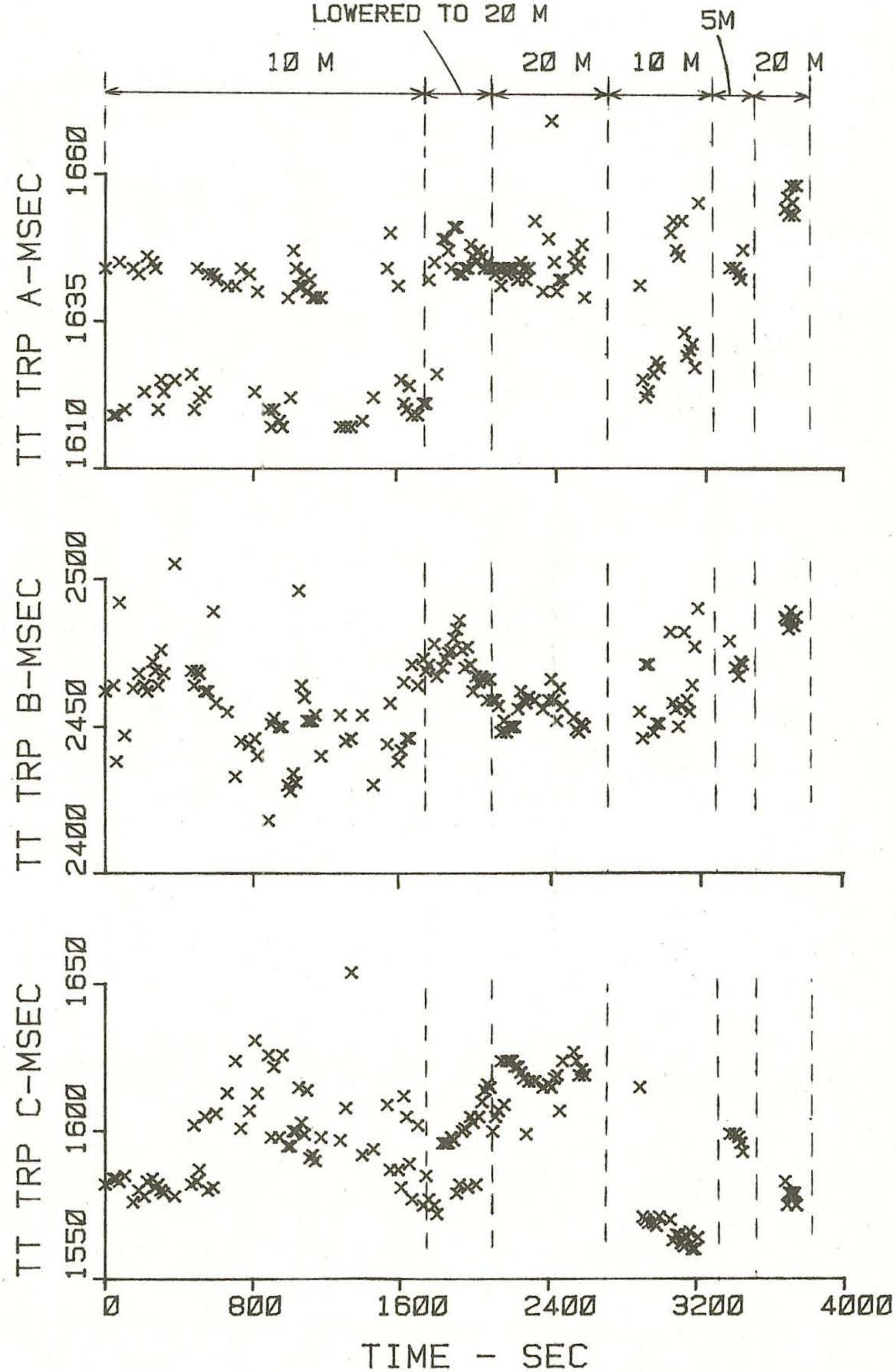

Figure 14. Ship cycle round trip travel times recorded during the August 13 experiment. Ship transducer depths are noted.

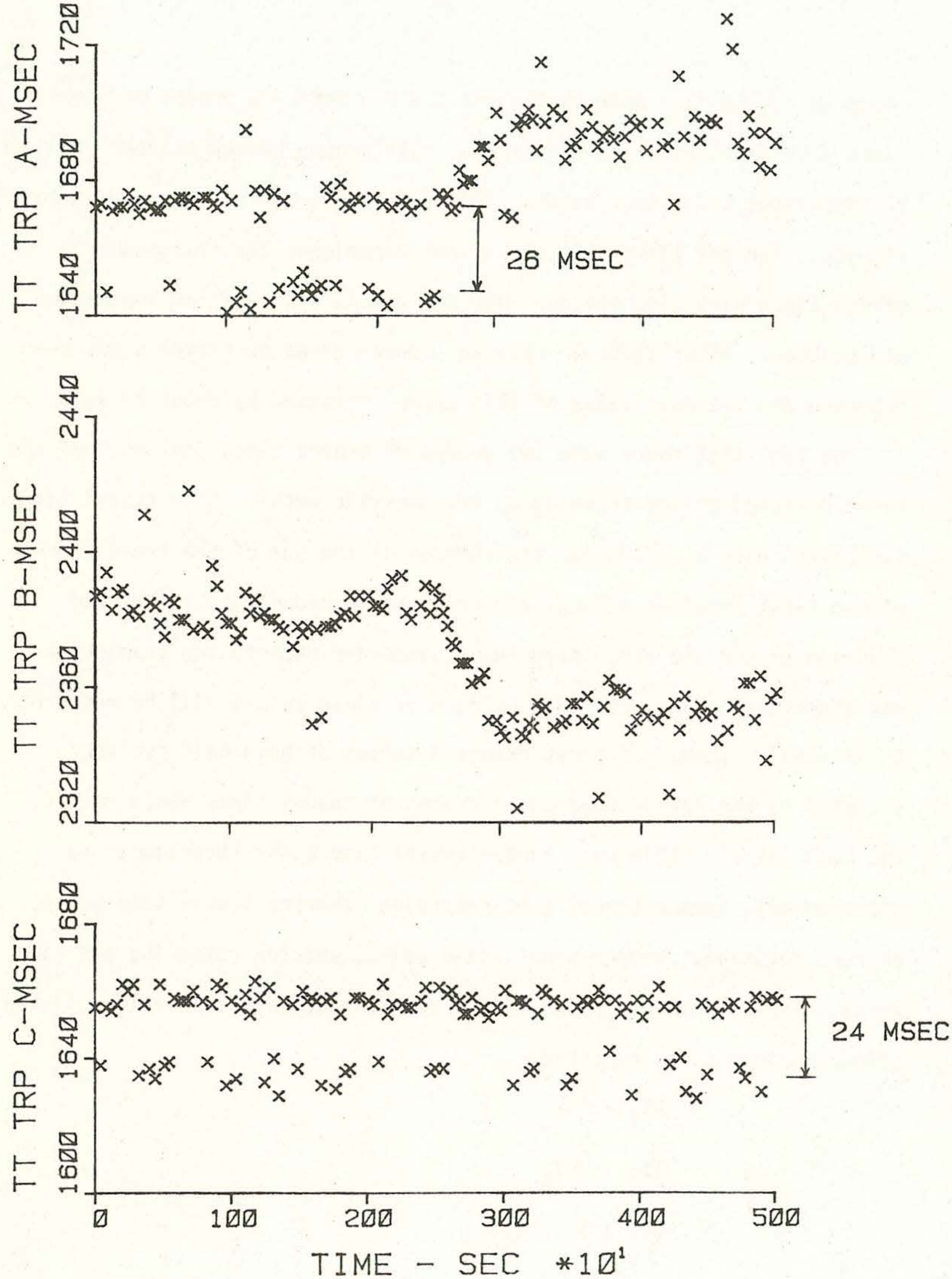

Figure 15. Ship cycle round trip travel times recorded during the August 14 experiment.

shown in Figure 13. Note that there are two definite groups of travel times associated with transponder C. Both groups have a scatter of about ± 5 msec about their mean value. The mean values differ by approximately 24 msec. For the first 2500 sec of the experiment the transponder A travel times were also divided into two groups with similar separation and scatter. After 2500 sec only the longer group of travel times were recorded and the mean value of this group increased by about 20 msec.

The fact that there were two groups of travel times implies that the first detected pulses traveled by two acoustic paths. Each travel time associated with a particular transponder is the sum of the travel times of two first detected pulses; one from the transducer to the bottom transponder and the other from the transponder back to the transducer. The transmission and detection of each of these pulses will be referred to as a half cycle. If first detected pulses of both half cycles traveled by two paths, four combinations of travel times would result. The combinations would be: longer travel time going (transducer to transponder), longer travel time returning; shorter travel time going, shorter returning; longer travel time going, shorter returning and vice versa. Three groups of round trip travel times, with mean values listed below, would thus be expected.

$$TT_1 = 2\ T_L$$

$$TT_2 = 2\ T_S$$

$$TT_3 = T_L + T_S$$

where T_L and T_S are the shorter and longer one way travel times respectively.

The observation of only two groups of travel times suggests that during one half cycle first detected pulses always traveled by the same path. The pulses first received during the other half cycle traveled by two paths. Those traveling by the shorter path were near the detection threshold of the receiver. For this assumption the possible combinations of round trip travel times would be:

$$TT_1' = T_F + T_L$$

$$TT_2' = T_F + T_S$$

where T_F is the travel time (one way) of the half cycle during which only one ray path was followed. The difference between the two groups of travel times would simply be $T_L - T_S$.

Because the transponders and the ship's transducer transmit at different power level and frequency and have different detection thresholds it is not unrealistic to assume that pulses which travel by a certain path may be occasionally detectable during one half cycle and always (or never) detectable during the other half cycle. The remainder of this section will be concerned with pulses transmitted and received during the half cycle for which two ray paths were presumably followed.

The travel time difference between the two paths should be in the order of 24 msec. During the July 14 experiment transponders A and C were about 1.2 km from the ship's transducer which was at 20 m depth. Figure 16 displays rays between the ship's transducer and a transponder at these approximate locations (calculated using the August 14 temperature profile, listed in Table 1). The corresponding travel times

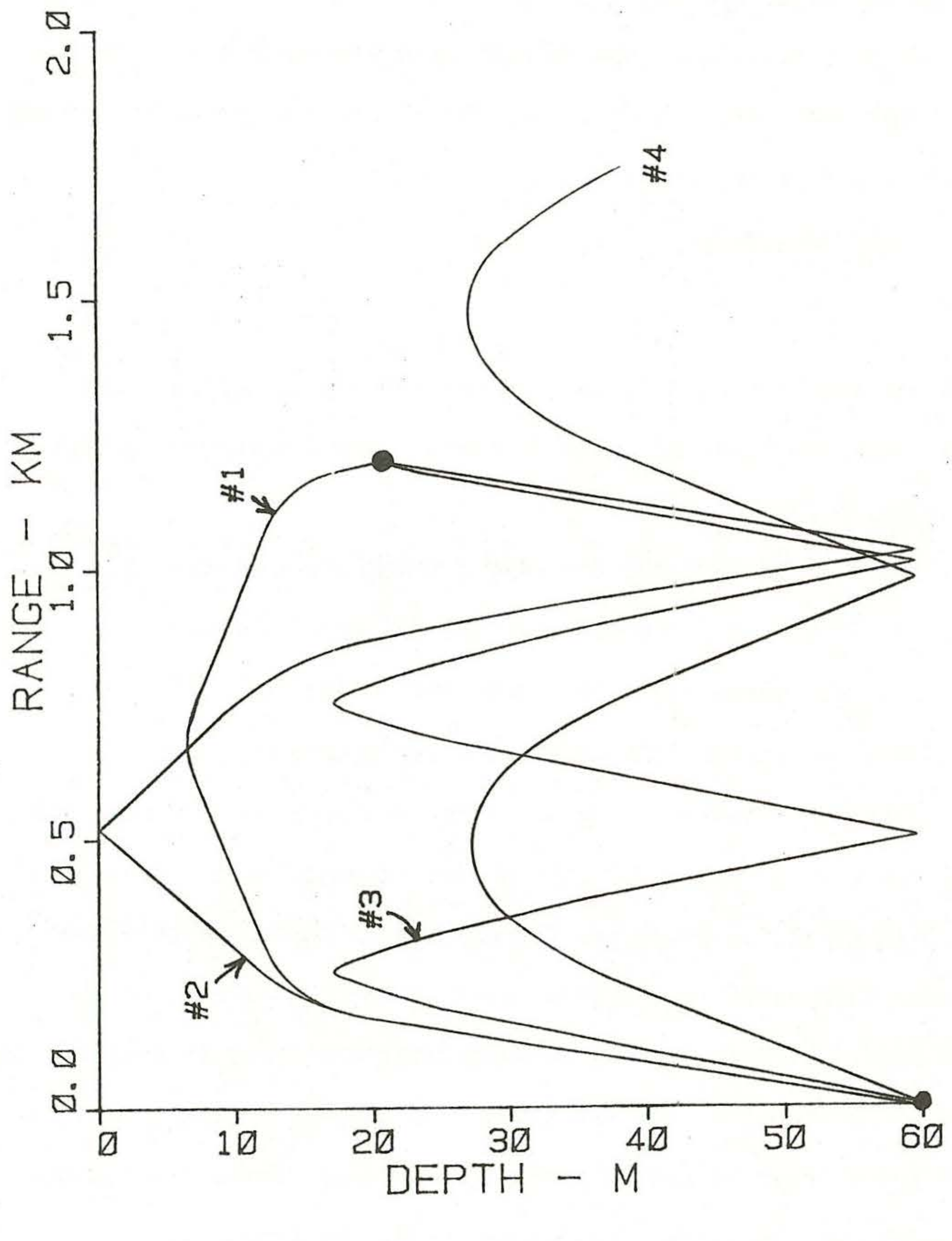

Figure 16. Acoustic rays calculated using the August 14 temperature profile of Table 1. Ray 1, 2 and 3 are transmitted and received between a bottom transponder at 60 m depth and a transducer at 20 m depth and 1.2 km range. Ray 4 is transmitted by the transponder at too shallow an angle to be received at the transducer's depth.

are listed in Table 2. The travel time difference between the inflected ray (ray #1) and the thermocline-bottom reflected ray (#3) is 27 msec. This would account for the difference between the two groups of travel times provided the surface-bottom reflected pulses (ray #2) were not detectable. These pulses would probably not have been detectable because they would have been weaker than the inflected pulses (due to longer path length and greater reflection loss) which were presumably near the receiver's detection threshold. This explanation is further supported by the conclusion drawn from Figure 12 that the bulk of the transmitted sound energy was trapped below the thermocline.

The loss of the shorter group of travel times associated with transponder A after 2500 sec was probably because the ship's transducer moved past the range where the inflected pulse was detectable (due to ship drift about the mooring). This would imply that at a range of greater than 1.3 km the bulk of the detectable pulses followed paths trapped below the thermocline. Note that the travel times associated with transponder B, which was 1.8 km from the ship, were not separated into two groups. There were, however, occasional pulses with travel time about 25 msec lower than the rest. Assuming that most of the transponder B pulses traveled by thermocline reflected paths, the occasional pulses of shorter travel time probably traveled by a path with one surface reflection (as displayed in Figure 12).

The explanation can also be applied to the travel times of the August 13 experiment (Figure 14). Note the transponder A travel times. With the transducer at 10m two groups of travel times were recorded.

Table 2

Computed values of the rays displayed in Figure 16.

Ray #	Travel time msec	Computed slant range*	Percent difference from true slant range**
1	797.2	1176m	-2.0
2	810.3	1195m	-0.4
3	824.4	1216m	+1.3

*Slant range = travel time x $\overline{SV}$

**True slant range = 1201m

Only pulses with the longer travel time were received with the transducer at 5m and 20m. An obvious interpretation is that at 10m the inflected and thermocline-bottom reflected pulses were recorded. At 20m the signal of the inflected pulse was just slightly lower than the detection theshold. At 5m the inflected pulse was not received, very likely, because it was bent away from the receiver.

For these experiments slant range was calculated by multiplying travel time by the average sound velocity of the water column. Slant ranges so calculated for the rays displayed in Figure 16 are listed in Table 2 together with the % error with respect to the true slant range. Note that the slant range calculated using the inflected ray's (#1) travel time is less than the true slant range despite the fact that the ray's path length is longer. This is because much of the path length is in the mixed layer where the sound velocity is greater than the average sound velocity. The error magnitudes for rays 1 and 3 are about equal to that predicted by the model of section 3 with an inflection range of 600m. Assuming that these were the actual paths traveled by the detected pulses the error in velocity determination due to slant range bias would be about 1%, as indicated by Figure 10.

It is interesting to note that the slant range error of ray #3 is nearly exactly predicted by the model of section 3 if modified so that reflection occurs at 18m depth rather than at the surface.

Ship and drogue positions for these experiments were calculted by a nonlinear regression method which used all three travel times. Drogue positions calculated using this method had less scatter about the apparent trajectory than did the corresponding positions calculated by a deterministic formula using only two travel times. Presumably the velocity error due to slant range uncertainty was also less.

Ship position components calculated from the August 14 data are displayed in Figure 17. The standard errors about the least squares regresson lines shown are

$$(\text{ST ERR})\text{east} = 7.2 \text{ m}$$

$$(\text{ST ERR})\text{north} = 5.4 \text{ m}$$

August 14 drogue velocity components were calculated as the slopes of the least squared linear regressions relating position component to time. The standard errors of the velocity components (slopes) ranged from 0.18 cm/s to 0.30 cm/s, values approximately equal to the standard errors calculated using data from a deep ocean experiment (Churchill et al, 1981). During all other experiments drogue trajectories were markedly curved. Velocity components for these experiments were taken as the slopes of quadratic regressions relating position component with time. The standard errors of these velocity components were generally less than 0.10 cm/s.

The navigation range during the experiments was approximately 4 km. This is appreciably different from the 8 km value measured on July 14. As will be shown by the following paragraphs, the difference can largely be attributed to thermocline depth, assuming that during at least one half navigation cycle the detectable pulses traveled by rays trapped beneath the thermocline.

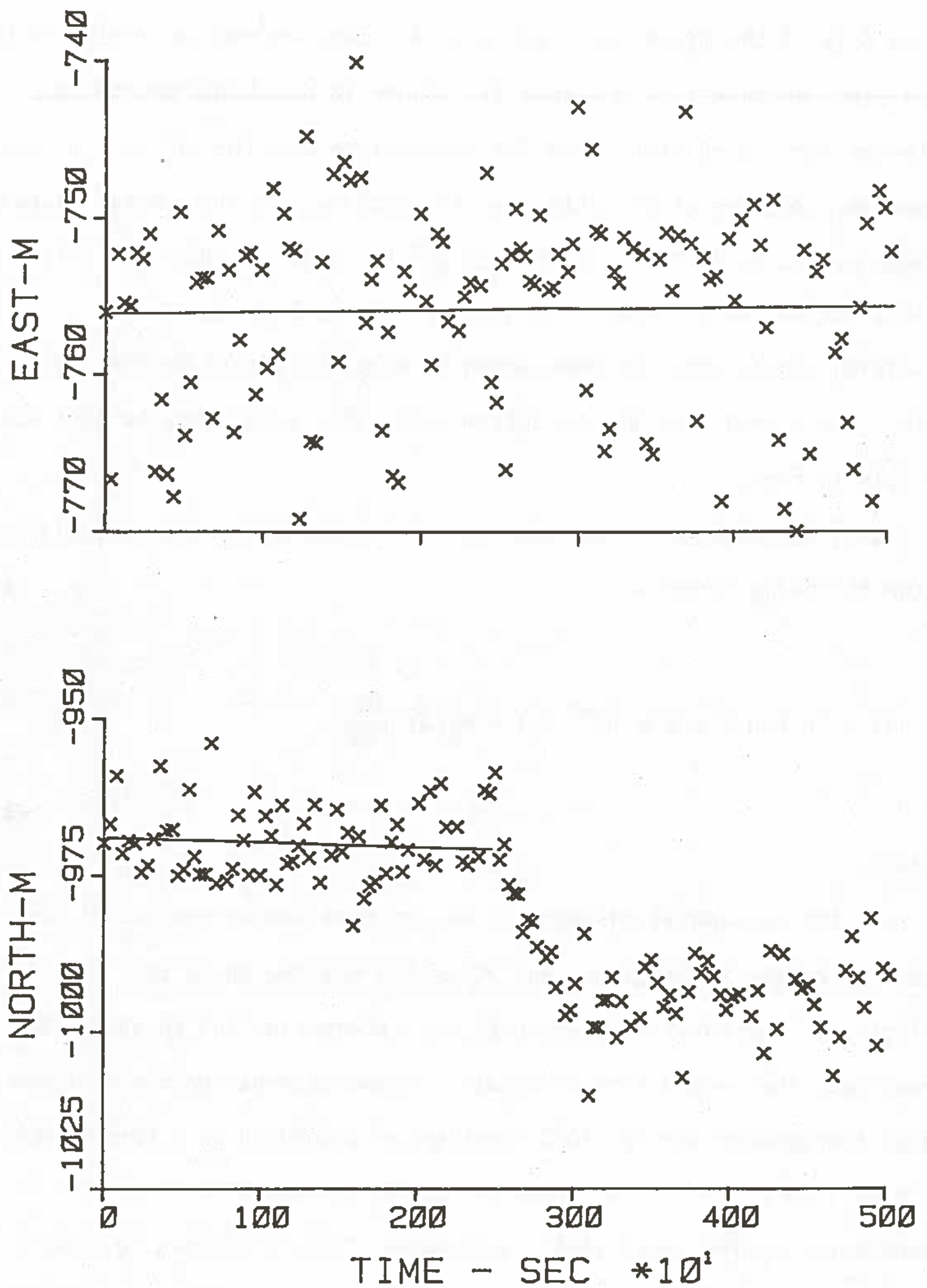

Figure 17. Ship position components vs. time calculated using the August 14 travel time data displayed in Figure 15. The lines are of least-squares linear regressions.

On July 14 the mixed layer was only 4 m deep whereas on August 14 the mixed layer depth was 14 m (Table 1). Figure 18 displayed thermocline reflected rays calculated using the temperature profiles of July 14 and August 14. Because of the shallower thermocline, the horizontal distance between bottom reflections is greater and the grazing angle at reflection is less for the July 14 ray. As discussed in Section 3, bottom reflection signal loss has been shown to be proportional to grazing angle. The signal loss due to bottom reflection would thus be less for the July 14 ray.

Signal attenuation of the two rays of Figure 18 has been calculated by the following formula:

$$ATT = 20 \text{ Log } r + 5 \times 10^{-5} (r) + N_B(4) \left(\frac{\theta_B}{10}\right)$$

where:

r is the horizontal distance, in meters, from the source, N_B is the number of bottom reflections, and θ_B is the grazing angle at reflection. The first term accounts for attenuation due to spherical spreading. The second term calculates volume attenuation for a 12 kHz signal transmitted through 10°C fresh water according to a formula given in Urick (1967). Signal attenuation due to bottom reflection is approximated by the third term. Reflection loss is assumed to have a value of 4 db at a 10° grazing angle and to be proportional to grazing angle.

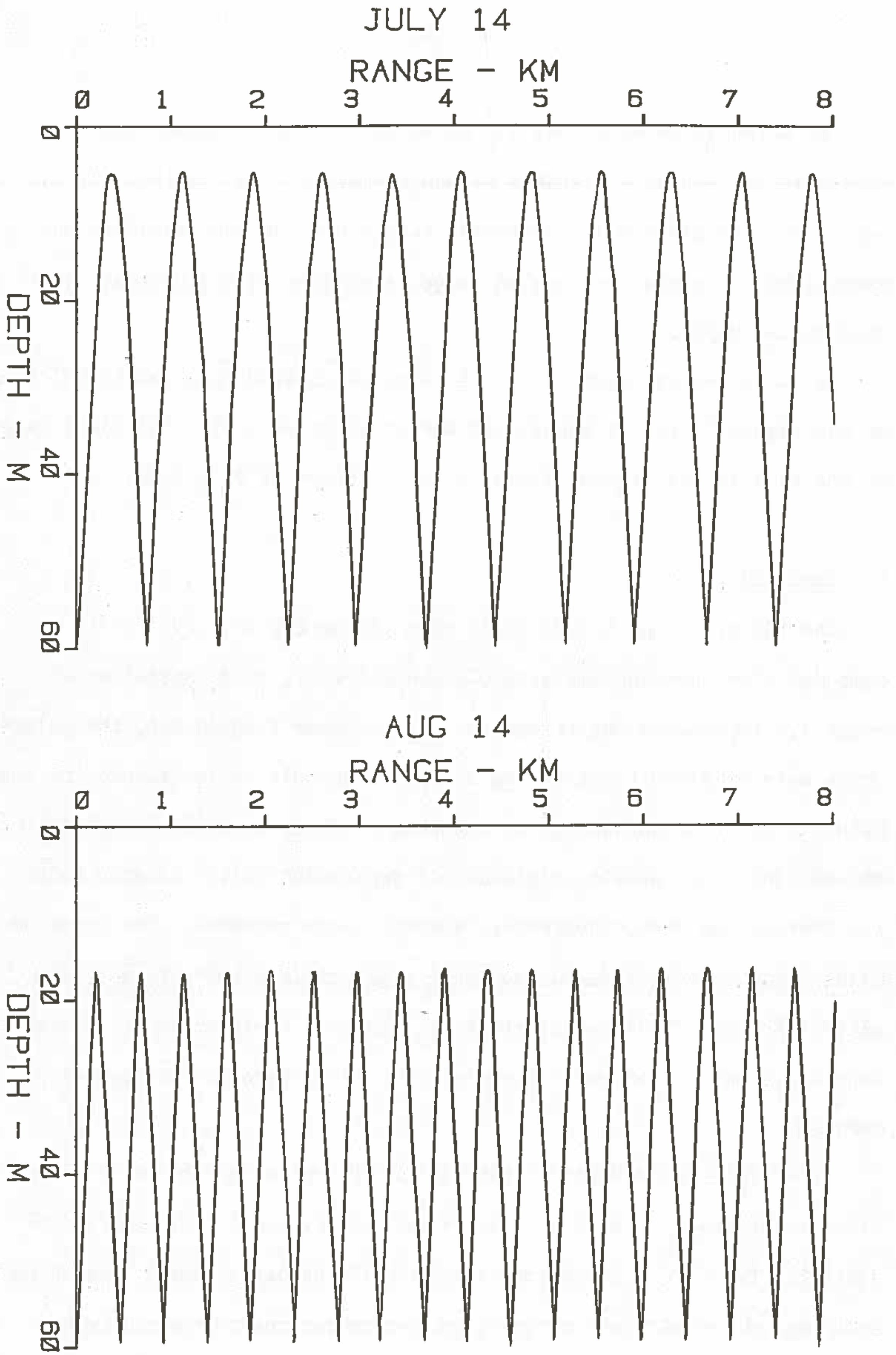

Figure 18. Acoustic rays, reflected at the thermocline, calculated using the July 14 and August 14 temperature profiles of Table 1.

The attenuation value was 112 db at distance of 4 km for the August 14 ray and at a distance of approximately 7 km for the July 14 ray. This calculation is admittedly crude; but, it does indicate an appreciable increase in tracking range associated with a decrease in thermocline depth.

It is noteworthy that the slant range calculated from the travel time of the August 14 ray at about 4 km had an error of 1.6%. The slant range of the July 14 ray at that distance had an error of only 0.8%.

6. Conclusions

The two groups of travel times observed in the ship cycle data combined with ray diagrams strongly suggest that, at a separation of about 1.2 km between the transducer and a bottom transponder, the pulses which were received first during a particular half cycle traveled by two paths, that of an inflected ray and that of a ray trapped below the thermocline. For greater distances of separation pulses trapped below the thermocline were, apparently, almost always received. The error in slant range determination using these rays was less than 2%; and, the associated velocity bias was about 1%. Because these presumed errors were very small an attempt to correct for slant range error was not merited.

For future experiments a combination of shallow depth and intense stratification may result in slant range errors too significant to be ignored. Devising a correction scheme would be particularly complicated with regard to the slant ranges used for drogue position calculation because for each slant range a total of four pulse transmissions and receptions are involved (the pulses transmitted to and from the bottom transponders during the most recent ship cycle, and the pulses transmitted from the transducer to the transponder and from the transponder to the sonobuoy during the sonobuoy cycle). Any method should be designed based on understanding gained from careful examination of the travel time data, ray diagrams, and other obtainable information.

Acknowledgements

I greatly appreciate the efforts of Bert Pade who developed the acoustic drogues and was the primary organizer of the Lake Huron project. I am grateful to Ken Peal, John Loud and Stan Rosenblad for their work on modifying the acoustic navigation system for drogue tracking. Special thanks go to Ken Peal who contributed his engineering expertise at the project site and who responded, most helpfully, to frequent requests for advice and suggestions. Useful advice was also obtained from Lincoln Baxter, Stan Bergstrom, Ping-Tung Shaw, Dr. Woolcott Smith, Dr. Robert Spindel and from my supervisor, Dr. G.T. Csanady.

All those who participated in the project at Lake Huron did so with dedication and enthusiasm. These individuals include: John Craft, Capt. John Crew, Bill Henley, Mike Kingston, Reed Payne, and Joel Pecchioli.

References

Churchill, J. H., B. H-G Pade and K. R. Peal, Water velocity measurement from nearsurface to 110m depth at deepwater dumpsite #106 using acoustically tracked drogues and conventional current meters, W.H.O.I. Technical Report, WHOI-81-11, 1981.

Csanady, G. T. and B. Pade, Coastal Jet Project, Environmental Fluid Mechanics Lab Rep. EFM1, Great Lakes Inst., Univ. of Toronto Rep #PR36, 1968

Liebermann, L. N., Reflection of sound from coastal bottoms, J. Acoust. Soc. Am., Vol. 20, 305, 1968.

Marsh, H. W., Reflection and scattering of sound by the sea bottom, J. Acoust. Soc. Am., Vol. 36, 2003, 1964.

Morse, R. W., Dependence of shadow zone sound on the surface sound velocity gradient, J. Acoust. Soc. Am., Vol. 22, 847, 1950.

Murthy, C. R., and J. O. Blanton, Coastal Zone Climatological studies of the Laurentian Great Lakes, proceeding second world congress, International Water Resources Association, New Delhi, Vol. 5, 431-448, 1975.

Urick, R. J., Principles of Underwater Sound for Engineers, McGraw-Hill Book Co., New York, p. 88, 1967.

Appendix

Acoustic Navigation System

The acoustic navigation system, used in these experiments, has been employed by WHOI investigators for a number of years and is well documented. Hunt _et al_. (1974) and Peal (1974) have provided an overall description of the system's design and operation. Sonobuoy tracking has been reported by Spindel and Porter (1974) and Spindel, Davis, MacDonald, Porter and Phillips (1974). The system will be briefly described in this Appendix.

The geometry of the system as used in Lake Huron is diagramed in Figure 19. The fundamental components are:

- a transducer lowered from the tracking ship (R/V _Coot_)
- three bottom mounted transponders
- a drogue connected to a listening hydrophone and tramsmitting VHF antenna
- a receiving antenna aboard ship
- a shipboard master timing clock, and minicomputer system which controls operation, processes incoming data, and displays computed positions
- a cassette tape recorder for data storage.

Two phases of nagivation "ship" and "sonobuoy" are performed as separate cycles.

The ship cycle is initiated with the transmission of a pulse (7.5 kHz, 10 msec) from the ship's transducer. Immediately following the detection of

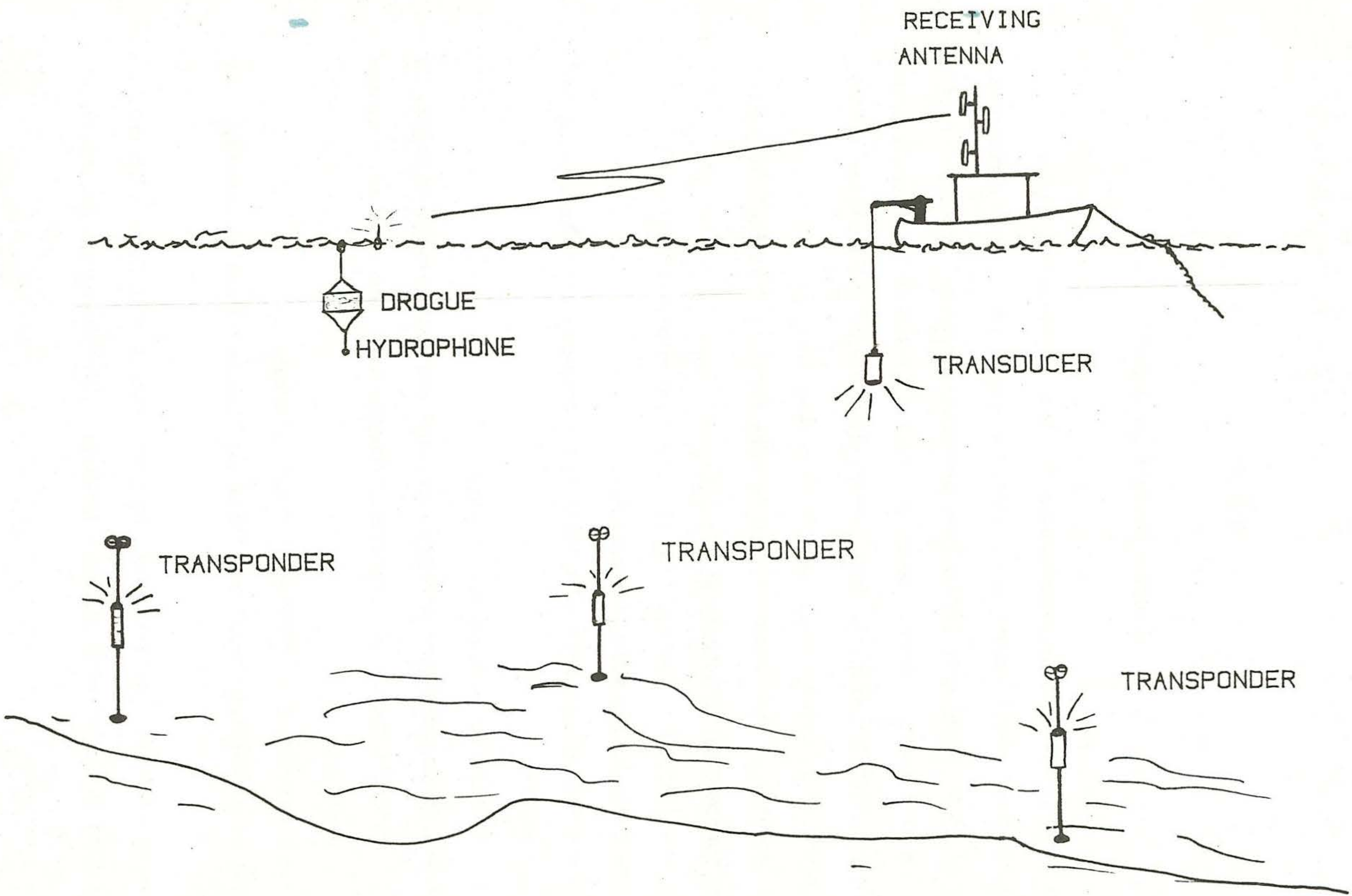

Figure 19. Geometry of a drogue tracking system with three transponders.

this pulse each bottom transponder generates a reply pulse at a specific frequency (11.5, 12.5 and 13.5 kHz). These reply pulses are detected by the ship's transducer. The acoustic round trip travel times between the ship and each bottom transponder are thus determined and logged by the shipboard computer. Slant range between the ship and each transponder is found by multiplying the one way travel time by the average sound velocity of the water column. The position of the ship relative to the transponder net is computed using an operator selected pair of slant ranges together with the known depth of the ship's transducer, the previously measured length of the baseline between the chosen transponder pair, and the transponder depths. The third slant range, if available, is used to resolve the ambiguity as to which side of the baseline the ship is on (otherwise, the side of the basline is specified by the operator).

The sonobuoy cycle also begins with a pulse transmission from the ship's transducer. The reply pulses from the bottom transponders are received at the drogue and transmitted (via radio) to the ship. Assuming the travel time from the drogue to the ship is negligible, the elapsed time between the initial pulse transmission and a reception at the ship is the acoustic travel time from the ship to the respective transponder to the drogue. The travel time from each transponder to the drogue is found by subtracting the ship to transponder travel time determined by the most recent ship cycle. These travel times are converted to slant ranges and used to calculate the position of the drogue with respect to the transponder net in the same manner as for the ship cycle. Ship and drogue positions are displayed in real time on an x-y plotter.

The transponder depths and the baseline lengths between transponders are determined by a survey in which travel times are collected from a number of locations and analyzed using a least-squares technique. Geographic positioning of the transponder net is accomplished using the ship's navigation system.

The procedure of alternating between ship and sonobuoy cycles yields a drogue position one to two times a minute. The normal practice is to track each drogue for about 5 minutes at a time. The present system can concurrently track 16 drogues (each transmitting at a different radio frequency). Constant attention is required. The operator must, among other duties, select which drogue is to be tracked and the transponder pair to be used for position calculation. An unpublished report on the system operation and the computer programs involved has been prepared by Loud (1981).

References

Hunt, M. M., et al., An acoustic navigation system, W.H.O.I. Technical Report, WHOI-74-6, 1974.

Loud, J. F., SHACK.2, SHIN.2 program documentation, Unpublished manuscript, 1981.

Peal, K. R., Acoustic navigation system operating and service manual, W.H.O.I. Technical Memorandum, WHOI-74-4, 1974.

Spindel, R. C., S. B. Davis, K. C. MacDonald, R. P. Porter, and J. D. Phillips, Microearthquake survey of median valley of the Mid-Atlantic Ridge at 36°30'N, Nature, 248, 577-579, 1974.

Spindel, R. C., and R. P. Porter, Precision tracking system for sonobuoys, IEEE Ocean 74 Symposium, Halifax, Nova Scotia, 2, 162-165, 1974.

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. WHOI-81-37	2.	3. Recipient's Accession No.
4. Title and Subtitle TRACKING NEAR SURFACE DROGUES USING AN ACOUSTIC TRAVEL TIME TECHNIQUE IN SHALLOW, HIGHLY STRATIFIED WATER - PROBLEMS AND OBSERVATIONS			5. Report Date May 1981 6.
7. Author(s) James H. Churchill			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Woods Hole Oceanographic Institution Woods Hole, Massachusetts 02543			10. Project/Task/Work Unit No. 11. Contract(C) or Grant(G) No. (C) DE-AC02-79EV10005 (G) 03-5-022-26
12. Sponsoring Organization Name and Address Department of Energy and NOAA			13. Type of Report & Period Covered Technical 14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

During July and August of 1980 near surface water velocities of Lake Huron were measured by tracking drogues, equipped with sonobuoys, using an acoustic travel time technique. Prior to these experiments difficulties associated with acoustic ray bending in the shallow, highly stratified environment were anticipated. Simple models were developed to predict the errors in drogue position and velocity determination resulting from ray bending. During the experiments round trip travel times of acoustic pulses transmitted between three bottom transponders and a transducer (lowered from a ship) were recorded. These combined with ray diagrams strongly suggested that, for a separation between the transducer and a bottom transponder of about 1.2 km, pulses which were detected first traveled by two paths, that of an inflected ray and that of a ray trapped beneath the thermocline. The error in position and velocity determination associated with these paths was 1 to 2%. Evidence also indicated that increased thermocline depth resulted in decreased tracking range.

17. Document Analysis a. Descriptors

1. Acoustic tracking
2. Acoustic drogues
3. Shallow water sound transmission

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages 49
	20. Security Class (This Page) UNCLASSIFIED	22. Price

(See ANSI-Z39.18)

OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

Woods Hole Oceanographic Institution Distribution List

Library
Marine Physical Laboratory
Scripps Inst. of Oceanography
San Diego, CA 92152

Library
Rosensteil School of Marine
and Atmospheric Science
Univ. of Miami
10 Rickenbacker Causeway
Miami, FL 33146

Library
Dept. of Oceanography and
Meteorology
Texas A & M Univ.
College Station, TX 77843

Library, School of Science
Oregon State Univ.
Corvallis, OR 97331

Fisheries-Oceanography Library
151 Oceanography Teaching Bldg.
Univ. of Washington
Seattle, WA 98195

Library
Inst. of Marine Science
Univ. of Alaska
College, AK 99701

Library
Dept. of Geography
Florida Atlantic Univ.
Boca Raton, FL 33432

Pell Marine Science Library
Graduate School of Oceanography
Univ. of Rhode Island
Kingston, RI 02881

Library
Inst. of Geophysics
Univ. of Hawaii
Honolulu, HI 96822

Marine Resources Reference Center
Mass. Inst. of Tech.
Cambridge, MA 02139

Chairman
Dept. of Earth & Planetary Sciences
Mass. Inst. of Tech.
Cambridge, MA 02139

Ms. Bettylou Rosen, Librarian
NOAA Miami Library
c/o Atlantic Oceanographic &
Meteorological Laboratory
15 Rickenbacker Causeway
Miami, FL 33140

Lindgren Library
Mass. Inst. of Tech.
Cambridge, MA 02139

Library
Chesapeake Bay Inst.
Johns Hopkins Univ.
Baltimore, MD 21218

Blue Hill Library
Harvard University
Pierce Hall - Oxford Street
Cambridge, MA 02138

Hancock Library of Bio. & Ocean.
Alan Hancock Laboratory
Univ. of Southern California
Los Angeles, CA 90007

Pearse Memorial Library
Duke Univ. Marine Laboratory
Beaufort, NC 28516

Library
Dept. of Oceanography
Florida State Univ.
Tallahassee, FL 32306

Library
Lamont-Doherty Geo. Observatory
Palisades, NY 10964

Library
Physical Oceanographic Lab.
Nova Univ.
8000 N. Ocean Drive
Dania, FL 33304

Library: Docs/Repts/Trans Sec.
Scripps Inst. of Oceanography
P.O. Box 2367
La Jolla, CA 92093

Library
Skidaway Inst. of Oceanography
55 West Bluff Road
Savannah, GA 31406

Commanding Officer
U.S. Coast Guard Ocean. Unit
Bldg. 159 E Navy Yard Annex
Washington, DC 20390

Mrs. Shirley Robinson
Library
The Oceanic Institute
Makapuu Point
Waimanalo, Hawaii 96795

Virginia Institute of Marine Science
Attn: Janice Meadows, Asst. Librarian
Gloucester Point, VA 23062

Woods Hole Oceanographic Institution
WHOI-81-37

TRACKING NEAR SURFACE DROGUES USING AN ACOUSTIC TRAVEL TIME TECHNIQUE IN SHALLOW, HIGHLY STRATIFIED WATER - PROBLEMS AND OBSERVATIONS by James H. Churchill. 49 pages. May 1981. Prepared for the Department of Energy under Contract DE-AC02-79EV10005 and for NOAA under Contract 03-5-033-26.

During July and August of 1980 near surface water velocities of Lake Huron were measured by tracking drogues, equipped with sonobuoys, using an acoustic travel time technique. Prior to these experiments difficulties associated with acoustic ray bending in the shallow, highly stratified environment were anticipated. Simple models were developed to predict the errors in drogue position and velocity determination resulting from ray bending. During the experiments round trip travel times of acoustic pulses transmitted between three bottom transponders and a transducer (lowered from a ship) were recorded. These combined with ray diagrams strongly suggested that, for a separation between the transducer and a bottom transponder of about 1.2 km, pulses which were detected first traveled by two paths, that of an inflected ray and that of a ray trapped beneath the thermocline. The error in position and velocity determination associated with these paths was 1 to 2%. Evidence also indicated that increased thermocline depth resulted in decreased tracking range.

1. Acoustic tracking
2. Acoustic drogues
3. Shallow water sound transmission
I. Churchill, James H.
II. DE-AC02-79EV10005
III. 03-5-033-26

This card is UNCLASSIFIED

Woods Hole Oceanographic Institution
WHOI-81-37

TRACKING NEAR SURFACE DROGUES USING AN ACOUSTIC TRAVEL TIME TECHNIQUE IN SHALLOW, HIGHLY STRATIFIED WATER - PROBLEMS AND OBSERVATIONS by James H. Churchill. 49 pages. May 1981. Prepared for the Department of Energy under Contract DE-AC02-79EV10005 and for NOAA under Contract 03-5-033-26.

During July and August of 1980 near surface water velocities of Lake Huron were measured by tracking drogues, equipped with sonobuoys, using an acoustic travel time technique. Prior to these experiments difficulties associated with acoustic ray bending in the shallow, highly stratified environment were anticipated. Simple models were developed to predict the errors in drogue position and velocity determination resulting from ray bending. During the experiments round trip travel times of acoustic pulses transmitted between three bottom transponders and a transducer (lowered from a ship) were recorded. These combined with ray diagrams strongly suggested that, for a separation between the transducer and a bottom transponder of about 1.2 km, pulses which were detected first traveled by two paths, that of an inflected ray and that of a ray trapped beneath the thermocline. The error in position and velocity determination associated with these paths was 1 to 2%. Evidence also indicated that increased thermocline depth resulted in decreased tracking range.

1. Acoustic tracking
2. Acoustic drogues
3. Shallow water sound transmission
I. Churchill, James H.
II. DE-AC02-79EV10005
III. 03-5-033-26

This card is UNCLASSIFIED

Woods Hole Oceanographic Institution
WHOI-81-37

TRACKING NEAR SURFACE DROGUES USING AN ACOUSTIC TRAVEL TIME TECHNIQUE IN SHALLOW, HIGHLY STRATIFIED WATER - PROBLEMS AND OBSERVATIONS by James H. Churchill. 49 pages. May 1981. Prepared for the Department of Energy under Contract DE-AC02-79EV10005 and for NOAA under Contract 03-5-033-26.

During July and August of 1980 near surface water velocities of Lake Huron were measured by tracking drogues, equipped with sonobuoys, using an acoustic travel time technique. Prior to these experiments difficulties associated with acoustic ray bending in the shallow, highly stratified environment were anticipated. Simple models were developed to predict the errors in drogue position and velocity determination resulting from ray bending. During the experiments round trip travel times of acoustic pulses transmitted between three bottom transponders and a transducer (lowered from a ship) were recorded. These combined with ray diagrams strongly suggested that, for a separation between the transducer and a bottom transponder of about 1.2 km, pulses which were detected first traveled by two paths, that of an inflected ray and that of a ray trapped beneath the thermocline. The error in position and velocity determination associated with these paths was 1 to 2%. Evidence also indicated that increased thermocline depth resulted in decreased tracking range.

1. Acoustic tracking
2. Acoustic drogues
3. Shallow water sound transmission
I. Churchill, James H.
II. DE-AC02-79EV10005
III. 03-5-033-26

This card is UNCLASSIFIED

Woods Hole Oceanographic Institution
WHOI-81-37

TRACKING NEAR SURFACE DROGUES USING AN ACOUSTIC TRAVEL TIME TECHNIQUE IN SHALLOW, HIGHLY STRATIFIED WATER - PROBLEMS AND OBSERVATIONS by James H. Churchill. 49 pages. May 1981. Prepared for the Department of Energy under Contract DE-AC02-79EV10005 and for NOAA under Contract 03-5-033-26.

During July and August of 1980 near surface water velocities of Lake Huron were measured by tracking drogues, equipped with sonobuoys, using an acoustic travel time technique. Prior to these experiments difficulties associated with acoustic ray bending in the shallow, highly stratified environment were anticipated. Simple models were developed to predict the errors in drogue position and velocity determination resulting from ray bending. During the experiments round trip travel times of acoustic pulses transmitted between three bottom transponders and a transducer (lowered from a ship) were recorded. These combined with ray diagrams strongly suggested that, for a separation between the transducer and a bottom transponder of about 1.2 km, pulses which were detected first traveled by two paths, that of an inflected ray and that of a ray trapped beneath the thermocline. The error in position and velocity determination associated with these paths was 1 to 2%. Evidence also indicated that increased thermocline depth resulted in decreased tracking range.

1. Acoustic tracking
2. Acoustic drogues
3. Shallow water sound transmission
I. Churchill, James H.
II. DE-AC02-79EV10005
III. 03-5-033-26

This card is UNCLASSIFIED